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THE DEVELOPMENT OF A GENERIC EXPERT SYSTEM FOR FAILURE ANALYSIS

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Abstract

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This thesis describes work carried out from October 1993 to October 1996 on the development of a generic expert system for failure analysis. The design and implementation of the expert system are discussed together with issues relating to the presentation of failure analysis expertise and diagnosis.

The aim of this project was to develop methodologies for the representation of failure analysis knowledge and information, within systems that aid the engineer to decide the reasons for the failure of engineering components and to suggest remedial actions. The building of a failure analysis expert system based on metallic materials failures was considered and found feasible, if undertaken by a hybrid approach of case based reasoning with additional rules. The collection and knowledge engineering of accurate and relevant information is central to this work, and methods of collection of this data through failure case histories and of checking their accuracy through expert system evaluation, datamining of online data bases and a user survey are discussed. Methods of dissemination are presented and developed into applications using multimedia, and the world wide web. All these applications illustrate methods, styles, and technologies suitable for use by engineers and academia to use the engineered 'failure analysis' knowledge to develop this expert system or other applications of their own and extend the understanding of failure analysis and so to reduce the propensity for failures.

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Chapter 1. Introduction

1.0 Introduction

Unexpected and premature failures of metallic structures are daily occurrences in industry. An engineer is expected to diagnose reasons for failure correctly and decide whether to redesign the component, change the material specification, manufacturing method or simply replace the failed component. However, it is likely that the engineer might not be aware of all critical failure routes, due to their complexity. This is not helped by the continuous development of new materials, designs and manufacturing processes all of which leads to new and unusual failure cases, with associated standards and legal issues. Thus the engineer is ill equipped to examine systematically the multitude of complex engineering material failure problems, such as fatigue, corrosion, etc. This, coupled with the lack of readily available information on the influence of design and manufacture on service performance and reliability, means that the failure modes and remedial solutions can be inadequately diagnosed, leading to a high propensity for failure to recur.

This thesis details the development of methodologies and knowledge engineering based around a computer based failure analysis diagnostic expert system. The expert system has been developed both as a design tool and a failure analysis tool which not only interactively identifies the failure modes and the critical factors in the design, processing, and end-use that cause failures to originate but also suggests methods to improve the reliability of the failed product by considering how materials, design details, and processing affect the propensity for premature failure. This novel approach is relevant to industry and educational establishments.

As the amount of knowledge continues to expand. The ability of a human expert to deal with large and significant problems decreases because of the limitations of human memory, yet the need for experts is thereby increased. Modern developments in information technology should allow this task to be made easier for the expert by storing and subsequently accruing this "experience" by using expert and knowledge base systems. The possibility of replacing the expert by a machine to process information has been explored by many authors, in books, journals, and science-fiction novels. To undertake this would require the machine to take on all the activities of the expert and be capable of exhibiting intelligence. Some time in the future this may be possible. However, presently, computers, are unable to replace experts,

because human experts can recognize the limitations of their knowledge, and use their creativity, to solve new problems. Also humans understand contextual and cultural issues in knowledge processing, while computers can only yield approximate results as everything has to be defined. Thus any advisory or expert system will in the best case scenario be a suggestive aid, until the processing power, knowledge acquisition and representation of computer systems improves drastically.

The application of expert systems to the task of failure analysis, and design against failure, is as complex as telling a lay-person to undertake a failure analysis from written instructions, in a very basic step-by-step process. However with the rapid developments in computer systems seen in recent years, just writing a software program is not worthwhile for future developments of other expert systems. Only through a detailed understanding of failure analysis, is it possible to develop a formalized model which can be used to represent failure knowledge for future expert and knowledge based systems, whatever their hardware and software configurations. Particular emphasis has thus been placed on the reasoning methodologies used, the knowledge domains for which these methodologies are appropriate, and the structure of failure analysis knowledge. Thus it is not just the process of building the expert system, but a process of refining, understanding and representing failure analysis knowledge and problem solving strategies that consultants use for the explanation, clarification, and tutoring, engineers on diagnosing metallic materials failure situations.

The thesis details the development of such an expert system for failure analysis. The literature review herein discusses typical expert systems architectures and their capability, followed by an analysis of different expert and knowledge based systems relevant to failure analysis. Finally an analysis of the different issues involved in failure and failure analysis investigation methodologies are given. It is only after the literature review and analysis, that assessing the feasibility of producing an expert system was possible.

During the research, the important aspect was to understand the knowledge engineering exercise undertaken to produce a prototype failure analysis expert system, from which through evaluation and further development it will be possible to built a complete expert system. However with new failure situations occurring, it is envisaged that evaluation and further developments will be a continuous process. Thus the general approach to using the failure

analysis expert system was discussed followed by techniques and the resulting component parts, such as the cases, questions, actions, and rules.

The terms expert and knowledge based systems can be interpreted broadly, to include other computer systems if they aid in the diagnosis process. Thus investigations into multimedia, and world wide web based systems were analysed. Datamining techniques were considered as a possible method to increase the accuracy of expert systems.

After an evaluation and discussion of the different programming tools produced in this work, suggestions are made on the viability of failure analysis expert system and the integration into other applications, and on possible future developments in this field.

Chapter 2 Expert System Architecture

2.0 Introduction to expert systems.

Expertise has always been a valuable commodity, built up by a specialist or expert over many years of experience in a particular area. As this expertise may be lost when the specialist moves to a different company or retires.Various means exist to pass on the expertise (Pireri and Nicholls, 1992). These range through appointing someone to shadow the expert during a period before the expert's retirement (designate appointment), writing reports and procedures, specialised publications, books, etc. It is natural, in today's environment, to consider how computer systems can be used to pass on expertise. Hence the development of computer expert systems which attempt to mimic the human consultant using "knowledge" that has been stored in the computer. These expert systems, although being a branch of artificial intelligence, are better thought of as a subgroup of knowledge based systems (Hayes-Roth, 1984) as indicated in figure 2.1.

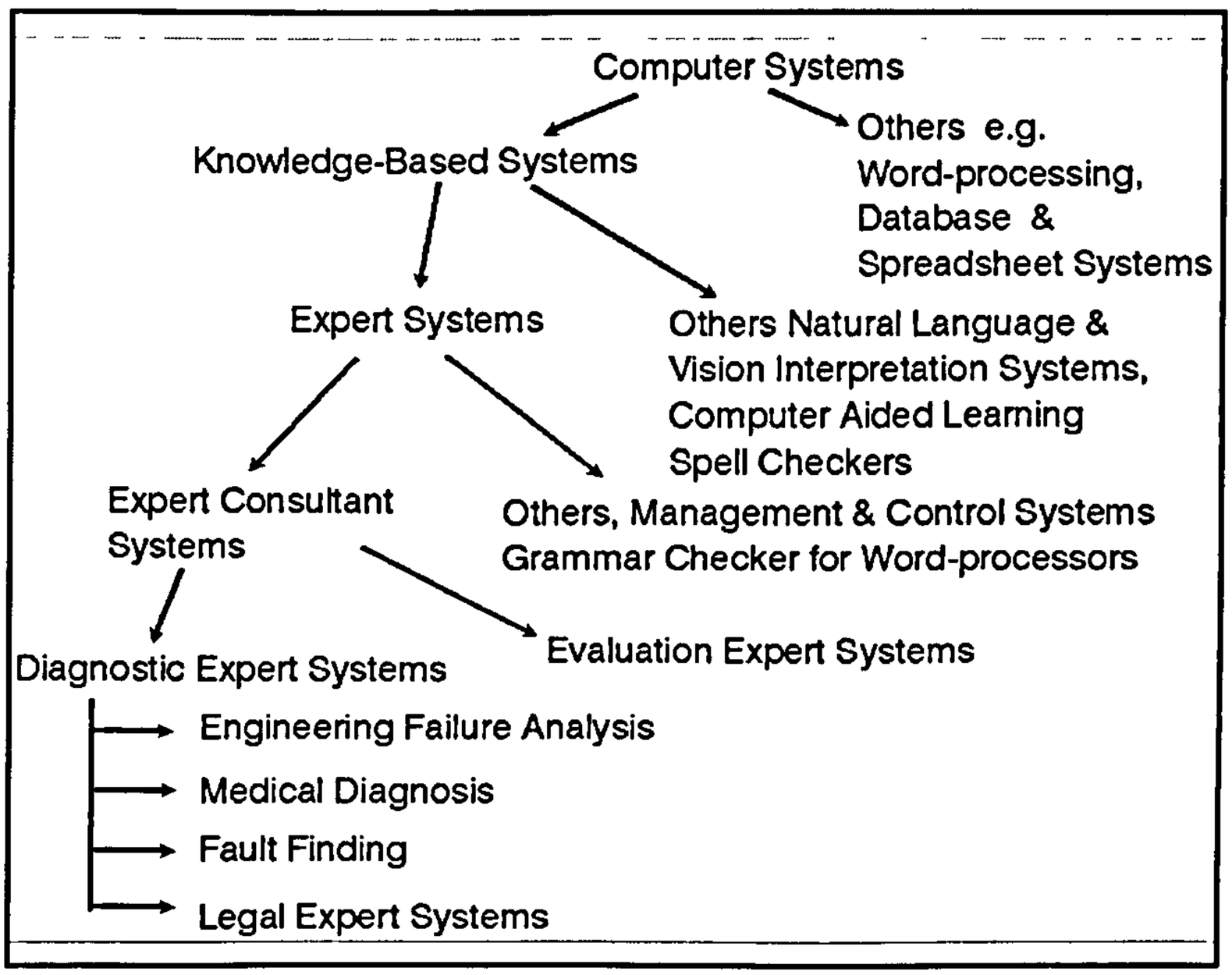


Figure 2.1 Computer applications schematic

In Engineering Failure Analysis as much as in any other field, Artificial intelligence (AI) promises revolutionary change. Many engineers are not entirely happy about this, and many have expressed great reservations as to the practicality and viability of Artificial Intelligence (AI) techniques to assist with failure analysis, and thus it has had little impact in engineering failure analysis. Also, AI itself has been given a poor reputation from the failure of over ambitious programming ideas; these are best kept within a science fiction novel.

When considering practical problems, such as failure analysis diagnosis, it is more realistic to consider all computer systems as decision support systems. The goal of a decision support system is to support the decision making process although not necessarily to provide sufficient information to make the decision an accurate fact. By the very nature of failure analysis

decision situations, it is unlikely that any methodology whether human or computerised could produce totally correct decisions in any case. There is always a small chance that a decision could be changed on receiving new information. Thus, a decision support system enables engineers to retrieve information in order to facilitate current decision making.

2.1 What is AI?

Artificial Intelligence (AI) is the science of making machines do tasks normally considered intelligent if done by humans. The machines in question are digital computers, but AI is not the study of computers. Rather, it is the study of intelligence in thought and action. Computers are its tools, because its theories are expressed as computer programs which are tested by being run on the machine. The main areas of AI include natural language understanding, pattern recognition, and problem-solving. The associated AI program types are natural language programs, neural networks and expert systems.

Expert systems and knowledge based systems techniques allow the modelling of intuitive knowledge, judgements, and experiences. These are better known as rules of thumb, which experts use with quantitative engineering knowledge (e.g. tensile strength, fatigue data) and algorithmic tools (e.g. fracture mechanics) to develop interactive diagnostic systems.

The crucial difference between knowledge based systems and expert diagnostic systems is that the technique used in expert diagnostic systems is the process of moving from known items of information or seen concepts to unknown information or unseen concepts by making inferences on the known knowledge. Both expert system and knowledge based system use rules of thumb knowledge, but knowledge based systems use symbolic representation of knowledge, whereas expert systems employ more algorithmic and statistical methods. An example of the differences is that a knowledge based system would be capable of conversing on the different modes of engineering failure, while an expert system in the domain of failure analysis, could provide a diagnostic forecast as to the most probable cause of failure of a component under particular environmental conditions.

Many computer systems can be called expert systems when they are only knowledge-based systems, and many computer systems can be called knowledge based systems when they are simple calculation programs. There is much exaggerated publicity within this area relating to the achievements of different programming tools. This is due to the commercial concerns associated with software development. It is important to look at what the programme does (i.e. its functionality) and compare this against your needs. Some computer systems can be called expert system or knowledge based system when they are just hypertext versions of a book. A knowledge based system and an expert system should be more then a hypertext book,

it should have an intelligent reasoning ability. If the wrong approach is used then the expert system will not achieve its diagnostic goal.

2.2 Expert systems architectures

An expert system is made up of the following components (figure 2.2):-

(i) The knowledge acquisition component is used to store knowledge as facts, rules, case histories and procedures in the knowledge base.

(ii) The knowledge representation component is used to elicit information from the knowledge base.

(iii) The user interface component is used to enter and elicit information through the processes of knowledge acquisition and knowledge representation.

(iv) The knowledge base has facts about the problem area. It also contains procedures to make logical deductions between symptoms and causes, e.g. mild steel components exposed to water result in the steel corroding.

(v) The blackboard is an area of working memory set aside for the description of a current problem.

(vi) The inference engine provides a methodology for reasoning about information in the knowledge base and in the blackboard, and for formulating conclusions.

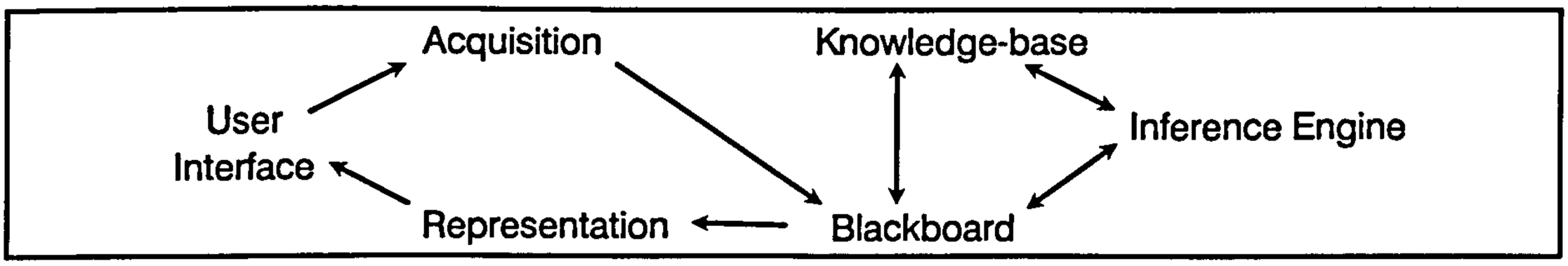


Figure .2 Typical expert system internal structure.

Recently expert systems have included an explanation subsystem or justifier between the inference engine and the user interface. The justifier aids the development, maintenance, and general understanding of the decisions taken by the expert system. It does this by tracing responsibility for conclusions by interactively answering questions such as the following:-

- Why was a certain question asked by the expert system?
- How was a certain conclusion reached?
- Why was a certain alternative rejected?
- What is the plan to reach the solution? For example, what remains to be established before a final diagnosis can be reached? (Turban, E., 1990)

2.3 Knowledge acquisition, representation, and graphical interface design

2.3.1 Knowledge acquisition (KA)

Knowledge acquisition (KA) sounds very simple and has been described by Buchanan et al., (1983) as "the transfer and transformation of potential problem-solving expertise from some knowledge source to a program", which generally involves the process of building the knowledge content into the knowledge base. The author considers this the most important aspect of building an expert system. There is an old saying which goes "What you put in is what you get out." Many researchers see knowledge acquisition (KA) as the bottleneck that currently constrains the development of expert systems (Berry and Broadbent, 1986). This relates to the problem of transferring the knowledge from documented and undocumented information. Documented information such as books, sensors, computer files, pictures, maps, flow diagrams, cause and effect analysis, laws and standards, have fewer problems in KA, because the information is already structured. Undocumented information resides in the minds of experts as personal knowledge. It is the job of the knowledge engineer to link the mismatch between the human knowledge structure and what is required for a computer program. There are a number of ways in which KA can be done as described above, but they all have the following generic problems: (Turban, 1990)

(i) A computer requires knowledge to be expressed at a lower, more detailed level than humans use.

(ii) Information error can arise in the transfer of knowledge if the expert knows little about computers and the knowledge engineer (programmer) knows little about the problem area. This problem increases with the number of participants such as the expert, the knowledge engineer, the system designer, and the user.

(iii) The expert is often unaware of the detailed process that he or she uses to arrive at conclusions, so may detail different rules, to the ones really used.

(iv) It is important to elicit the structure as well as the knowledge as one without the other is like a telephone directory not alphabetically ordered.

(v) It may be difficult for the expert to express experiences regarding a process or technique, especially when they are made up of sensations, thoughts, sense memories, and feelings. The human expert expressing knowledge and the way the computer/expert system expresses knowledge are generally very different.

(vi) Lack of time, planning and cooperation on the part of the participants.

(vii) The complexity of testing, refining and validation of the knowledge.

An ideal KA system has been outlined by Hill et al. (1986) which concluded that

(i) a system of direct interaction between the expert and the expert system without intervention by the knowledge engineer is preferred.

(ii) a system should deal with a board class of problem domains, rather than a narrow problem domain. Also, it should be flexible and capable of being upgradeable to a different broad domain.

(iii) a system should be intuitive thus eliminating the need for prior training of the user. (i.e. commands should be obvious and easy to assimilate)

(iv) a system should analyse work in progress to detect inconsistencies and gaps in the knowledge.

(v) a system should incorporate multiple sources of knowledge.

(vi) a system should communicate easily with different expert systems and other programs, applications, etc.

(vii) And finally to facilitate the above, a system should have a friendly user interface.

2.3.2 Knowledge representation

There are two fundamentally different methods of representing knowledge: as programs, which are called procedural, and as data, which are called declarative. Procedural knowledge representation is where knowledge is embedded in programming code. It is context dependent, making these systems hard to understand and hard to upgrade or modify. Declarative representation is context-independent. It encodes knowledge as data, which is less heavily encoded and easier to understand, which leads to ease of modification.
Each method has its place. Procedural encoding brings about faster execution. The difference being analogous to the difference between compiled and interpreted code. Furthermore procedural encoding gives the programmer full control, where declarative schemes relinquish control to the system; this can be difficult to predict and control. The combined benefits of ease of understanding, ease of modification, and semantic clarity, even at the expense of a slower execution speed and a certain loss of control, have been found to be too important to do without in expert systems. Consequently, most expert systems employ some form of declarative representation (Sell, 1985). A full detailed discussion on knowledge representation is out of the scope of this thesis. A more detailed analysis of the complexities of knowledge representation can be found in Sell (1985), and in Shapiro (1990)

2.3.3 The user interface

The key to a successful and well-used computer system is a very simple user interface. Unfortunately, most systems are designed for computer literates. Some people will belittle others who look at computers and the promise of unlimited power, and think that working a programme should be easy. Computer users like to think that they have something special. With the development of faster and better computers, it is well within the scope of developments that anyone with no training will be able to use a computer. The user interface is the link between the complex machine code and the user undertaking and performing a task.

As an expert system is to be used by a non-expert to gain a quick solution to a problem, the user does not want to spend time in learning how to use the system; it should be self-evident. Thus it can be said that the design of the user interface is very important, especially for expert systems and knowledge based systems.

At the time of writing (1997), software and hardware vendors have been putting more and more effort into user interface design and it is estimated that more than 50% of new developments in computer systems will be in this area. From the traditional methods of menus and commands interaction there is a move towards object manipulation, natural language, speech understanding.

2.3.4 User interface techniques

To understand the advantage in using one technique over another, it is important to understand the techniques for user interfaces.

2.3.4.1 Command language, is where the user enters commands such as "run, save, load" etc., which are generally seen as verb-noun combinations such as run program_A, save results_A, etc. This includes the execution of function keys (F1.....F12) and macros.

2.3.4.2 Menu interactions, require the user to select from a list of possible choices the required function/command to undertake a given task. This is seen in many applications such as word-processing (WordPerfect 5.1), spreadsheet programs (Lotus 123), etc.

2.3.4.3 Question and answer interactions are where the computer or the user asks questions to acquire information and/or for the clarification of a point of fact. The user or computer prompted by the question responds by a sentence or phrase, which could be picked from a menu of options. This could be as simple as "yes" or "no", or more complex as in describing a manufacturing processing technique. This technique of interfacing has been used a lot in expert systems, knowledge based systems and other information based systems.

2.3.4.4 Form interactions (fill-in-the-blanks) are where the user enters data or commands in designated spaces (fields) in a form in response to the headings on the form. This technique can be seen on many database systems.

2.3.4.5 Object manipulation, the best example of this technique is the Microsoft Windows user interface environment (Windows 1.. 3.1....Windows 95). Objects, represented by symbols known as icons, are manipulated by either a mouse or cursor to preform tasks held within the objects programming (scripts).

2.3.4.6 Natural language (NL) processing is the branch of AI that focuses on getting computers to understand spoken (**voice** recognition, NLVR) or typed English. This is now starting to emerge as a viable alternative for people to communicate with computers and it is seen as the most preferred technique for user-computer interactions. Presently natural language interaction using the keyboard to type in English commands is well established and is used in a commercially available expert system program (CBR Express by Inference corporation.). Within the next 10 years, desktop PCs will routinely respond to our spoken requests with answers in perfectly spoken English - or any other language but currently (1995) this is still at its early stages in which a training time for each user is required by the computer so it can understand the voice commands. (T. Green, 1995)

2.3.4.7 Handwriting-recognition interfaces have been recently developed by several computer companies. These companies have produced commercial products in which after a time the computer learns to understand a user's handwriting. At present they have had limited success in the fields of electronic organisers and personal digital assistants, but it is envisaged that more success will be gained in data logging for surveys and warehousing. (Computer Shopper, December 1993.)

2.3.4.8 Visual interactive modelling uses the visual display unit (computer screen) to show a representation of a system or process in which decision making or problem solving can be undertaken. The number of variations is enormous, but when integrated with object manipulation, this becomes a very powerful tool. An example of this can be seen in many manufacturing simulation applications, finite element analysis, and more recently virtual reality interface programs.

2.3.4.9 Hypertext and hypermedia are two terms relating to the handling of textual and graphical information via nonlinear links to other textural and graphical information sources. Hypertext relates solely to text and graphics, where hypermedia relates to a documentation that could contain several types of media, including text and graphics, but also including audio, and video information. The idea of hypertext and hypermedia is that by object manipulation, where the object is either text or a graphical image, a link is made to another source of media. An example is where the user wishes to find out more information on steel manufacturing from a hypermedia document on materials. In the main text the mouse is used to point and then click on a word such as steel, through a database of links all references to the word steel are displayed. This could be a video of steel production, or other graphical/textural information. The idea is that the users can control the level of detail they wish to examine and undertake quick searches related to the reader's interests. Hypermedia has developed over the last few years, with more programs being released each month especially relating to knowledge based applications and computer assisted learning packages for students.

Examples of packages and their applications are Toolbook and Microcosm, which were used to produce a phase-diagram computer aided learning package. (Hall, J.L.; et al. 1994), (Bailey, J.D.; et al. 1994), and NASA's "Mosaic" or Natscapes' "Navigator", which is used on the World Wide Web (WWW). The WWW is used for graphical internet access.

2.3.5 A comparison of user interface techniques

A comparison of techniques was initially done by Majchrzak et al. (1987) and developed by Turban (1990, pp648), which is included in table 2.1, to which the author (Graham-Jones, J) has added the dimension of computer training time that is to be distinguished from user training time, and the techniques of Question and answer; Natural language, NL (typed); NL with Voice recognition, NLVR; Handwriting-recognition interfaces, HRI; Visual interactive modelling; Hypertext and hypermedia. The additions were based on the author experience in this field and conversations with other researchers. The author felt that the previous work by Majchrzak et al. (1987) and Turban (1990, pp648), had not taken into account the recent developments in user interface techniques and the availability of the hardware to a wider audience. Therefore, as well as some new dimensions and techniques, some of the conclusions differ in the dimensions and techniques mentioned by Majchrzak et al. (1987) and developed by Turban (1990, pp648).

Dimension	Techniques			
	Command	Question and answer	Form	Menu
Speed	Fast	Slow at times	Medium	Slow at times
Accuracy	Many errors	Error free	Medium	Error free
User training time	Long	Short	Medium	Short
Computer training time	None	None	None	None
User preference	Prefer, if trained (only)	High	Low	High
Power	Very high	Medium-High	Low	Low-med
Flexibility	Very high	Low-Medium	Very limited	Low-Medium
Control	The user	Computer and user	Computer	Computer

Dimension	Technique		
	Object Manipulation	Natural Language	NL and Voice recognition
Speed	Could be slow	Slow at times	Medium
Accuracy	Error free	Some errors at present technology	Many errors at present technology
User training time	Short	Short	Medium
Computer training time	none	depends on system	Long for each user
User preference	Very high	High	med
Power	Medium-high	Medium-High	Medium-high
Flexibility	Very high	Low-Medium at present technology	Medium at present technology
Control	The user and computer	The user and computer	The user and computer

Dimension	Technique		
	Handwriting recognition interfaces	Visual interactive modelling	Hypertext and hypermedia
Speed	Could be slow	Slow at times	Medium
Accuracy	Many errors at present technology	Few errors depending on model quality	Error free
User training time	Short	Medium depends on system	Medium
Computer training time	Long	Depends on system	None
User preference	Low at present technology	High	High
Power	Medium-high	Medium-High	Medium-high
Flexibility	Medium at present technology	Low-Medium at present technology	Medium at present technology
Control	The user and computer	The user and computer	The user and computer

Table 2.1 Comparison of different user interfaces

2.3.6 Guide lines for user interfaces

Cox and Walker (1993) gave an excellent and detailed account for guide lines for the dos and don'ts in user interface design, for the development of a computer system. As expert systems are to be used by non-experts, the design of the interface is most important. So for Cox and Walker (1993) the following rules have been developed to relate to user interfaces in expert systems:-

1. Make it clear and concrete and not abstract, i.e. user maps and icons rather than a matrix or abstract numbers/letters.

2. Make as much information as possible visible to the user, rather than invisible.

3. Allow copying of data rather than having to recreate data.

4. Allow choice from a list rather than filling in a blank space.

5. Allow interactive changes and additions rather than completing at the end of a run or batch.

6. Design the system to fit the user's conceptual and cognitive model of the task.

7. Be consistent throughout, i.e. use the same symbols, graphical layout, icons and definitions. Also use universal commands such as, Move, Copy, Delete, Show properties, Copy properties, Again, Undo, Help. These universal commands are detailed in Common User Access guide lines that should be followed in all systems. For IBM computer systems see reference. IBM (1989)

8. Give the user control to vary all interactions rather than forcing the user to respond in one way, i.e. there are many ways of writing the date, allow for them all.

9. Allow for user modifications of a system, through default and setup systems.

10. Allow short cuts for experts, i.e. hot keys and pull down menus.

11. Use common language that describes the function/task rather than computer jargon.

12. Motivate the user to use the system. This can be achieved by not producing ambiguous errors or having excessively long period without providing positive feedback. Do not punish the user for making a mistake.

13. Allow seeing and pointing rather than remembering and typing.

14 If applicable, use a WYSIWYG environment, (What You See Is What You Get)

15. Keep things simple, with clear directions and messages.

16. Automatically close down completed or non required, steps, windows and other items.

17. Allow easy reversal of functions and tasks as users will change their minds after a function has been executed. Also, allow easy correction of errors.

18. Prevent errors by understanding and allowing for common variations, i.e. I, ! or i instead of 1.

19. Make the system easy to learn. Whiteside et al. (1985) demonstrated that easily learnt products were also easy-to-use products.

20. Reduce short term memory loads by using strategies and techniques rather than remembering words, facts or numbers, i.e. list the last few documents the user worked on rather than the user having to look them up. Up to four items in memory should be considered the maximum.

21. Make sure the screen layout is understandable, not too cluttered but not lacking in information. This is a very important and complex field, guide lines on screen layouts can be found in Galitz (1989). Also Tufte (1990) details ways to show information on paper, many of which are relevant to screen layouts. This is very important when captions and multi-data-entry fields are used, as poor layout can lead to mistakes.

22. Divide dialogues into digestible sections.

23. Use colours but only a few that are colour coordinated and can be changed by the users.

24. With advancing technology sound and voice (speech) recognition is an important communication device. Where possible use sound but be careful about its use and give the user control. A simple setup could produce a click or tink-a-bell when an OK button is pressed and a dull thud when a cancel button is pressed.

25. Finally, if unsure of a feature leave it as a "user" option.

2.4 Inferencing Methodologies

There are several inferencing methodologies, i.e. various ways in which matching can be achieved. These are, rule based, model-based, and case based reasoning (CBR) as shown in figure 2.2.

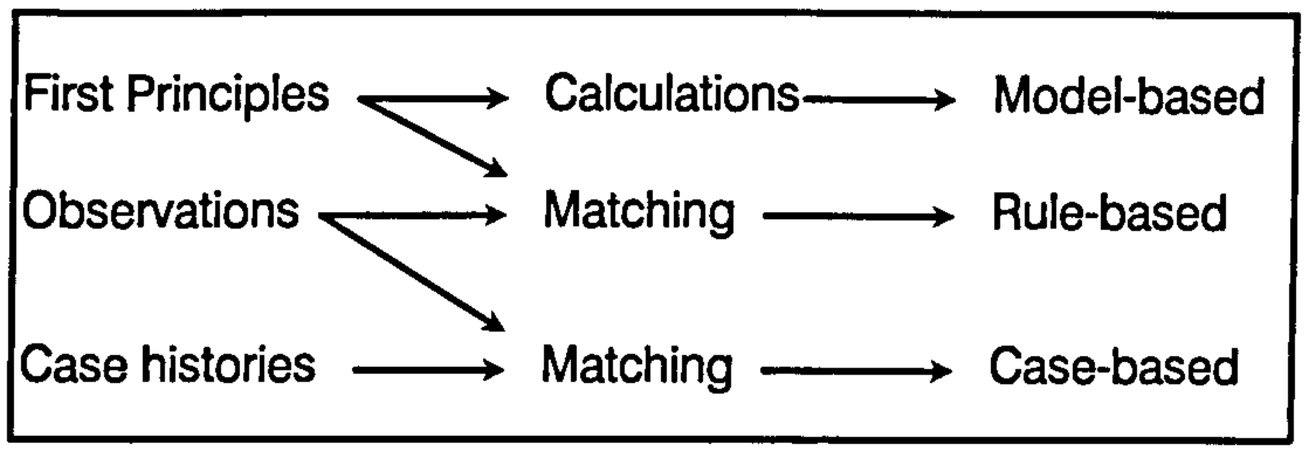


Figure 2.2 Inferencing Methodologies.

2.4.1 Rule based systems

These types of expert systems are based on knowledge represented in the form of condition-action pairs. IF this condition occurs, THEN some action will occur. The firing condition could be the result of other conditions occurring. For example IF condition (x) AND condition (y) THEN do action (z) ELSE do action (q). The idea is that this is a simple simulation of the cognitive behaviour of human experts. Although simplistic in their initial structure, they can be developed into highly complex structures with considerable artificial intelligence. Thus, they are the most common reasoning methodology. An example, in the field of failure analysis, could be "IF there is a cyclic load AND the component is in a corrosive environment, THEN corrosion fatigue may be a problem, ELSE, fatigue is a problem and corrosion is not".

There are many different expert system shells in existence. One of the first was Mycin developed in 1973 as a medical diagnostic tool for certain antimicrobial infections and to recommend drug treatments. A detailed review of Mycin and other expert systems with their associated architecture can be found in Johnson and Keravnou (1988) and in Harmon, Maus and Morrissey, (1988)

Forward chaining rules:- This is the basis of a rule based expert system, in that it uses the IF condition THEN do action. The forward chaining uses the IF with input from the user, which is usually observations and facts. To which the expert system then reasons in a series of forward chaining steps to the solution. The output from one rule may become the input to another rule and hence the rule set will forward chain until a solution is found. If no solution is found, the system might ask the user for more information to continue the reasoning process.

Whenever then rules:- This reasoning methodology is a sub set of forward chaining. However, any rule can fire when the conditions are met, rather than firing in a set sequence. It uses the WHENEVER condition (x) applies THEN do action. This action could set of another

rule and this could be any rule from the list of rules. Thus whenever rules have a single hirechical structure where others have mult hieritical structures.

Backward chaining rules:- This is the bases of a rule based expert system, in that it uses the IF condition THEN do action. The backwards chaining rule uses the consequent or THEN part of a rule and reasons in reverse. The rule often predicts states rather than actions, e.g. IF condition (x) THEN state (y) applies. User input in this case is a description of a state that exists and the system then has to backwards chain to find the conditions which have allowed that state to exist. Simply put the solution is given and the expert system finds the conditions required to give the solution.

2.4.2 Model based system

The term model-based reasoning is used to include all systems with an explicit model of a problem, including systems relying on heuristic, causal, statistical and mathematical models that depend on knowledge of structures and the behaviour of devices or systems. Thus they work from first principles, e.g. Stress = Force over Area. Although rule based systems are a subgroup of model based systems, rule based systems are far more common and are seen separately as they rely on heuristic rules that represent an expert's knowledge. Model-based systems are largely experimental and have been overtaken by case based reasoning. Model-based systems can be very complex and are best used in linear calculations and programmes. They do not undertake matching on minimal information as do rule based and case based systems.

The majority of expert systems are based on explicit models of knowledge. These models can be of great detail and are generally based on first principles (deep causal model, Clancey, 1985). However, an explicit model of a domain must still be elicited and implemented. This generally takes the form of rules or objects, but despite their success many developers of model based knowledge-based systems have met several problems, as detailed below (Watson et al., 1994).

i) Knowledge elicitation is a difficult process, being often called the "knowledge elicitation bottleneck".

ii) Implementing knowledge-based systems is a complex and difficult process requiring special skills, which often takes many man-years.

iii) Once implemented model-based knowledge-based systems are often slow and are unable to access or manage large volumes of information.

iv) Also, once implemented, they are difficult to maintain (Bachant and McDermot, 1984)

Many solutions to these problems have been sought through better techniques, software tools and improved methodologies (Watson et al. 1994). However, human problem solving is based somewhat on past knowledge and experiences. It is the application of that knowledge to a current problem that experts use to solve problems. In heuristic systems, as detailed in sections 2.4.1 and 2.4.2, knowledge is compiled as rules or models. The compiled knowledge is developed from general rules of thumb, general procedures and processes, that the experts have developed over their years of experiences. An expert can generally remember compiled knowledge, and probably only a few past problem-solving cases, unless the cases have occurred often, then the expert can assimilate compiled rules, or build models.

Typically, when an expert undertakes a problem, there might not be the compiled knowledge to hand or the problem is too complicated. In which case, the expert looks for similarities between what his problem is and any past explicit knowledge cases. This is most notable in the law courts where past cases are used to find a solution. In failure analysis, case histories are also used as there are so many factors involved, with the exception of a few standard failures the problems become too complex. Thus, in complex or unknown problems past explicit knowledge is used.

2.4.3 Case based reasoning

Case based reasoning is a new approach to decision automation. The concept of case based reasoning is based on the idea of using explicit, documented experiences and adapting them to solve new problems from previous experiences (J.L.Kolodner, R.L. Simpson, K. Sycara, 1985), (Watson et al.1994). Case based reasoning provides both a methodology for building systems and cognitive models of people undertaking decisions. It is consistent with much that psychologists have observed in the natural problem solving people do. However, people although good at using analogues and cases to solve new problems, they are not always good at remembering the correct ones. However, computers are good at remembering. Thus within a computer system, case based reasoning (decisions aiding) is a methodology in which people and computers work together to solve problems. The person does the actual decision making using cases stored within a computer, as guide lines. (J.L. Kolodner, 1991)

This reasoning method has increasingly attracted more attention because it seems to address the problems outlined in section 2.4.2:-

1) Case based reasoning does not require an explicit domain model and so elicitation becomes a task of gathering case histories
2) implementation is reduced to identifying significant features that describe a case, an easier task than creating an explicit model
3) by applying database techniques, large volumes of information can be managed

4) Case based reasoning systems can learn by acquiring new knowledge as cases thus making maintenance easier
5) Case based reasoning can dramatically reduce the costs of developing, maintaining, and running expert systems. Below, is described what case based reasoning is and why it is important for the expert system developer.

Traditional expert systems attempt to model human problem solving expertise as a purely deductive process. They develop a unique new solution to each problem. But there is evidence to say that human experts do not work in this manner. Instead they remember and adapt solutions from previous problems. Given this observation, a few artificial intelligence researchers have focused on solving problems by retrieving previous solutions rather than generating new ones. Case based reasoning, compares a current case to a library of cases with known solutions. Case based reasoning has been applied to a range of classification and construction tasks. It is particularly useful in tasks where a formal set of rules for generating solutions is difficult to obtain, but examples of correct solutions are readily available.

These "previous solutions" are stored as "cases" in a case base. The case based system can be used for multiple purposes, including training and decision automation. When a search fails to locate a similar case, the search itself becomes the basis for a new case, in effect "learning from experience". Because of this, a case based reasoning system can keep pace with a changing environment, eliminating the need for repeated software upgrades performed by knowledge engineers. Because of the simple knowledge representation, little expertise is required to maintain the system. The case base manager does not need to be a programmer.

The advantages of the case based reasoning approach are particularly evident in terms of a consultant's decision support system for client enquires. Organizations are increasingly besieged by clients whose requests for help and information overwhelm available technical resources. Addressing clients' problems quickly and effectively is critical to an organization's reputation and competitiveness. Many organizations are therefore establishing centralized consultancy facilities, where representatives of the organization are available to answer questions and solve problems posed by the clients.

The traditional components of such a system are a telephone call management system, a problem-tracking database, and paper/on-line documentation. However, this support does not provide the representatives with the diagnostic knowledge they need. This reduces the client's satisfaction, in the short term, because answers to pressing problems are not addressed immediately, and in the long term because engineers are repeatedly diverted from their primary tasks to answer inquiries from the support organization.

In a case based reasoning system for decision support, knowledge about the client's problems and their resolutions are stored as cases. Cases are indexed by features that describe each case. These features are fundamental to the success of a system. It is a considerable research challenge, to discover these features, and how they inter react. Roberge et al (1996) has detailed a few problems related to indexing case based system. (Roberge, Tullmin, Tretheway, 1996 InterCorr/96). However indexing these features is the major bottleneck in knowledge acquisition, which has been attempted within this thesis.
When presented with a description of a problem, this is entered into the system, and the closest-matching cases are retrieved from case memory. Also this should be used to generate questions to be asked of the client to confirm or eliminate possible solutions. Because the retrieval process can identify partial matches (as opposed to the exact matches in a traditional database system), the system can work in the presence of incorrect or incomplete information from the client. The eventual response to the client is based on the solution(s) of the cases that are most similar to the client's current situation.

Because of the simple representation of knowledge as cases, users can maintain their own system and keep it current with the set of problems and solutions coming in from the field. This eliminates the rapid obsolescence that occurs in expert systems built with traditional software. They can expand the system incrementally without the need for repeated software upgrades performed by knowledge engineers.

2.4.3.1 Case based reasoning expert system shell, CBR Express.
CBR Express is a tool for case based reasoning. CBR Express is an application of ART-IM, the Automated Reasoning Tool for Information Management from Inference Corporation. ART-IM is an advanced artificial intelligence programming tool. It stores and retrieves cases that represent customer problems, mechanical parts, legal precedents, corporate policies, or any other type of discrete object that is required to be stored and found again quickly.

It is particularly good at finding cases that the operator cannot easily describe. The program accepts a natural language sentence as its initial input, and then presents a menu of questions to the operator to elicit more specific information about the desired object. Since the program takes the initiative in this dialogue, untrained operators can learn to perform searches in a matter of minutes.

It employs a selection of sophisticated matching algorithms to find all cases that are similar but not necessarily identical to the search description by measuring the similarity of text strings and of numeric values required for writing natural cases.

The difference between CBR Express and conventional database software is its ease of use. A traditional database requires a knowledgeable operator who can set up queries in a format understood by the software and appropriate to the fields of the stored records. Field names and desired values must be entered correctly. With CBR Express the initial search uses unconstrained natural language, and the words do not even have to be spelled correctly. Then the software generates the queries and poses them to the user, instead of the other way around. The expert knowledge resides in the program not in the operator.

2.4.4 Case based styles

Apart from the mechanical aspects of case definition, i.e. the actual data or facts to be included, the behaviour of case based systems, will depend on the case based system styles' uses and their suitability for the intended application.
Will the system be making decisions, or only supporting them? Will the operator be a domain expert, or someone with no special knowledge of the subject? Is there more emphasis on reducing search time, or on making good selections even with mistaken input values? Is the search looking for one case, or for a set of cases? These are the types of questions associated with different fundamental styles.

There are two common fundamental case based styles: exclusive and inclusive case based systems, (CBR-Express reference manual)

Exclusive case based systems, where the output of the system is expected to be a *single case.* An example is an application where the operator has very limited expertise and the system has to make a decision. Typically speed is essential in this type of system. These are case bases for diagnosis and identification that really allow only one solution at a time. We call these "exclusive" case bases because their purpose is to discard potential cases rapidly until one good solution is found. In these systems, a "good" solution is expected to have a very high similarity match, typically between 70% and 90%. In terms of an application this requirement is often combined with a pressing need for rapid resolution, both in terms of search efficiency and operator throughput.

The fundamental assumption is that there is likely to be a single fault, and the job of the system is to isolate it as rapidly as possible. This, "rapid isolation" refers more to guiding the operator to a solution in the least possible number of steps. Therefore the questions which appear in most of the cases have either a **Yes** or a **No** answer that immediately partitions the case based system into different faults. Answer Yes, for instance, and watch the list of questions immediately focus towards one type of fault. Sometimes a single question will diagnose the problem uniquely.

Inclusive case based systems, are where the outputs of the system are a set of cases. The operator of such a system is expected to browse the matching cases for information that contributes to his or her understanding of the current situation. An example of this system is one that helps a lawyer locate multiple legal precedents that seem to bear on the current case or another system that helps a designer locate previous designs, whether they were successful or not but relate to the present design problem. In the usual situation, a thorough, inclusive search is more important than speed for this type of system.

In the inclusive case base style the system presents the user with a palette of possibilities, but makes no strong recommendations. We refer to these systems as "general" associative-retrieval systems. High-scoring cases may have a low similarity match, e.g. scores as low as 15% or 20%, since in these systems even weak similarities are of interest. Frequently this type of case based system supports applications where the concept of an "action" or "recommendation" hardly makes sense.

Case bases for design, decision support, argumentation, inventory search, and prediction typically supply the operator with supportive information rather than with definitive decisions. The operator of such a system is frequently an expert in the domain and uses the system as a "memory bank" of previous experiences, available options, parts in inventory, and so forth. This type of system is generally not under the kind of time constraints found with a typical help-desk project.

The behaviour desired of this system is to pull in even weakly matching cases, and never to eliminate a case simply because it does not quite match the search criteria. For instance, an engineering designer contemplating the design of a luxury sports car for young executives, complete with a turbo charged engine, five speed gear box, open top construction, might be interested in any case that mentions the "sport car", a turbo charged engine, five speed gear box, or the open top construction There is no requirement that the search criteria all be satisfied by a particular case. To produce this behaviour in CBR-Express one simply avoids the use of mismatch weights, (-) absolute scoring, and absence scoring. Then one sets the max-matches parameter to the maximum number of cases that seems practical (to a maximum of 100 for CBR Express and 30 for CasePoint). Finally, one designs the cases to use relatively few questions, relying instead on the case description to seek out the interesting cases. The questions can be used to fine-tune the search. For instance, the questions might be used to limit a search for failure criteria to those that pertain to a particular material.

Another point about "inclusive" systems is that the operator's interaction with the case based system is more exploratory than with "exclusive" systems. The operator may try searching on

several different descriptions, with or without various questions answered. There is no assumption that the search should converge rapidly on a specific set of cases. Instead, a typical session might involve several exploratory searches, each of which may turn up one or two cases of interest.

This does not imply that a given case based system must fit one of these descriptions. In most cases it is a mixture of these two styles, but between them they cover the behaviour desired of systems for help desks, planning, diagnosis, classification, identification, and evaluation of proposed actions.

2.5 Reasoning methodologies

Heuristic reasoning, qualitative reasoning, and quantitative reasoning

Besides the different reasoning methodologies, different levels and types of knowledge can be required in a computer system. These are Heuristic reasoning, qualitative reasoning, and quantitative reasoning. Heuristic reasoning uses a symbolic approach to define problems, generate hypotheses, and draw conclusions. A symbolic approach is similar to the approach taken by human experts and the way they think when first looking at problems. An example might be a human expert looking at a rotating shaft. The possibility of fatigue would undoubtedly occur to him. At a somewhat higher level of knowledge is qualitative reasoning which construct, validates, and refines the analytical models. In the same example above qualitative reasoning would be used to work out which method is appropriate to calculate the fatigue life of the rotating shaft by considering the many different factors such as stress raisers. Finally full quantitative reasoning performs numerical analysis and evaluates the results, such as being able to complete a Paris law calculation to predict fatigue life for a measured crack size. Going from the holistic approach through to quantitative reasoning requires a greater depth of knowledge and produces a more complex expert system. Qualitative and quantitative reasoning is not required in many diagnostic failure cases and thus not in a general expert system, because a complex answer with many numeric values is often not required, but just a YES or NO answer. For example, Question:- Will mild steels fully immersed in sea water corrode? Answer:- Yes. With qualitative reasoning the rate could be asked; answer :- approximately 0.13mm per year. Quantitative reasoning could give details of the amount of corrosion over the service life of the component. However, this might not be required. It is likely that the expert wants to know whether or not corrosion will occur or not. The question as to the amount of information required is extremely important, and depends on the preferences that the users of the expert system have. This has been explored within the thesis, by surveying the possible users and is covered later. However, there is a clear relationship between the type and level of educational background and the amount of knowledge required.

Most expert systems are in the field of diagnostic consultants for a particular domain of knowledge such as medical diagnostics, legal case analysis, etc., as shown in figure 1. Historically expert systems in a consultancy role are generally used by nonspecialists to obtain specialist advice to increase their understanding in a domain. Therefore, considerable knowledge is required. Casnet, Internist, Mycin, Prospector, Heuristic Dendral and others fall into this category (Barr and Feigenbaum, 1982) The accuracy of the recommendation/solutions depends on the quality and quantity of the knowledge-base and responses to requests from either the computer or the user. Diagnostic ability is necessary, but not sufficient by itself. Ultimately, an expert system should explain the results, learn new things about the domain, restructure the knowledge to tune the results, and break rules whenever necessary. The first of these should be in all expert systems, but the others are presently still being developed at the research level (Turban, 1990). However, to mimic true human expertise it will be necessary to include all of these features in new expert systems.

Chapter 3 Expert Systems Applied to Failure Analysis

3.0 Introduction

In the field of expert systems related to failure analysis there has been little work and few commercial products. To understand this and to understand how a failure analysis expert system should work it is important to understand the successes and failures of other diagnostic expert systems. Several expert systems presently available and in development have been detailed below.

3.1 Different computer aided failure analysis systems

There are no computer aided failure analysis systems systems that fully encompass a true generic expert system, but there are several systems that could aid in failure analysis, be that at the design stage or after failure. Of the expert systems and knowledge based system presently available, the majority can be split into domain-type failure systems, mechanism-type failures (Corrosion, Fatigue, etc.), and expert systems related to national, industrial or military standards. Most of these systems have been developed as design tools, rather than failure analysis systems. This is because developers of systems have historically thought that new designs stem from innovative and novel ideas, i.e. first principles rather than from the experiences of unsatisfactory and faulty design. A good expert system will use past knowledge of failures as well as working from first principles. Though most of these expert systems are design based tools, they can still be used for failure analysis, in that, in a given situation, the factors acting on the component could be entered into the expert system. This would give different levels of feedback. At low levels this would be a "yes or no" answer as to whether failure was going to occur. At greater levels of information, the expert system could give the reason, mode and type of failure to occur and this could be checked against the failure.

The majority of these expert systems have been developed for a number of reasons such as:- a company or institute (Governmental, educational) with a problem; a university research project; by an institute, (NiDI, NACE, etc.), advertising and promoting its field of interest. Apart from the latter, few of these expert systems have come on the open market. The reasons are many but range from lack of sufficient funds to develop the system fully; the company or institute internal competitive policy; lack of an achievable goal/objective; out-of-date and non-upgradable software/hardware; too complex and unworkable systems; lack of knowledge within the availability of systems. For these reasons expert systems have been either given a bad name or have been overlooked as useful, i.e. they promised more than they achieved.

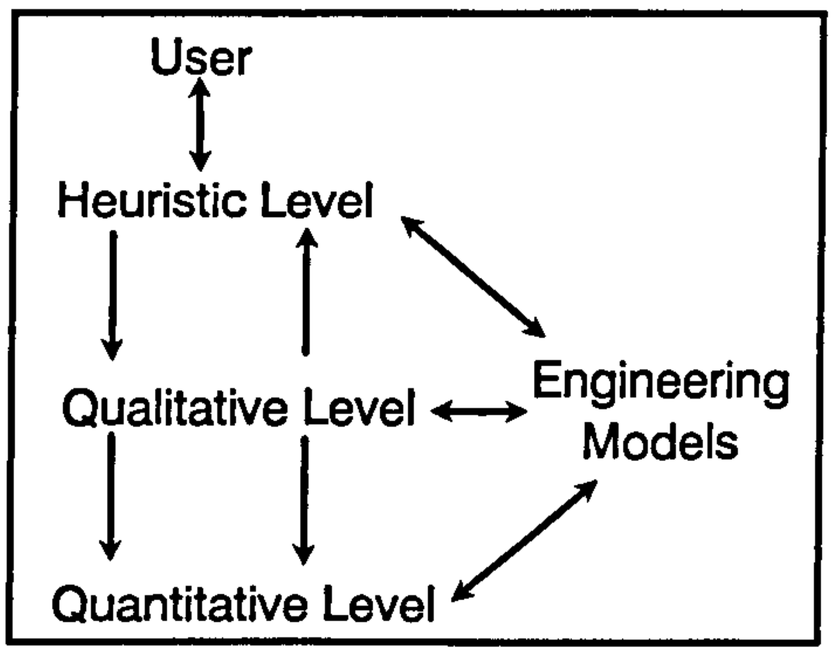
3.1.1 Expert systems built around standards

Several expert systems are built around a standard. They are initially developed for clear commercial reasons of financial gain and to develop a greater perceived quality in a product or service. The important aspect relating to expert systems built around standards, is that they are easier to sell especially if they have been developed by an institute or a quality awarding body. Typical examples are Fatigues, *and* Crackwise produced by The Welding Institute (TWI). Fatigues automates the British Standards Institute (BSI) Published Document PD 6493:1991 for fatigue assessment procedures of weld flaws under dynamic loading. Crackwise automates BSI PD 6493:1991 levels one and two fracture assessment procedures of weld flaws under static loading using fitness-for-purpose criteria. These expert systems are successful due to the well known and very limited domain that has been captured. There was also considerable support in their development because a high fee paying market was considered available.

3.2 Domain type failure analysis systems

3.2.1 Bearings

Walton (1992) developed an expert system to diagnose probable causes for bearing failure. Using a large cell matrix of bearing failure symptoms and related causes. Each cell within the matrix contains a zero to 100% confidence level that such a symptom would suggest a given cause. This confidence level has been detailed by a bearings expert. The user answers questions, which update the matrix and at progressively more advanced levels of diagnosis, interim lists of probable causes are produced. The user could accept or reject any or all the causes and has access at all times to detailed explanations and remedial screens.



.Figure 3.1 Reasoning levels,

This is an excellent example of where an expert system has been quickly developed by using a matrix system on a known quantity of failure causes and failure symptoms. This method is generally only successful in a limited domain. For example, bearings where there is a known quantity of knowledge.

3.2.2 Bridges

Kim Roddis et al. (1992) has developed a failure analysis expert system to diagnose fatigue and fracture in steel bridges, called CRACK. CRACK is based around the domain of flat plate girders that support bridges and explains a failure by matching a crack progression sequence to the observed facts. Fracture mechanics calculations are undertaken to determine critical crack size and fatigue life. The important difference between this application, which

probably explains its success, and others is the fact that it reasons on three sequenced reasoning levels, heuristic, qualitative, and quantitative, linked by an engineering model of the physical structure of the bridge, (Figure 3.1).
There are several other expert systems related to bridges such as:- FASTBRID (Fatigue Assessment of Steel BRIDges) developed by Melhem and Wentworth (1992), which is a prototype expert system that conforms with FHWA (USA Federal Highway Administration) guidelines, so to provide problem solving and provide personnel training on bridge fatigue failure problems. The Bridge Fatigue Investigator (BFI) is a knowledge-based expert system using a hybrid object-oriented approach developed in Prolog by Chen, and Wilson, (1989).
Some bridge expert systems act as supporting systems for a bridge inspector, so the correct inspection, evaluation and repair can be preformed, (Horiguchi and Iwamoto, et al. 1990) (Horiguchi and Nakamura, et al, 1990)

3.2.3 Boiler tube failures

Singh and Bains (1987) developed a user-friendly expert system for diagnosing boiler tube failures in fossil power plants known as ESCARTA. It was designed to emulate a human expert in boiler tube failure analysis, which would be used by non-experts to determine the tube failure mechanism, by providing preliminary leads into conducting root-cause analysis and to recommend corrective actions. The knowledge base in ESCARTA uses information contained in Lamping and Arrowood (1985), which categorized six major classes of failure mechanisms and a further 22 basic boiler-tube failure mechanisms, together with the opinions of experts with many years of boiler failure experience. This information was developed into "IF-THEN" rules. The important aspect of this expert system is the categorizing of the different failure modes, as required in a generic failure expert system.

3.2.4 Spur gears

Su et al., (1993) developed an expert system for the tribological failure diagnosis of spur gears, using IF-Then rules and a very user-friendly graphical interface. It was developed by National Cheng Kung University, Taiwan, and the Chinese Petroleum Corp., Chia-Yi, in Taiwan. A friendly graphical user interface is very important for non-experts' use. This is explained in the section on user interface design.

3.2.5 Aircraft maintenance

Many expert systems have been developed for improving aircraft maintenance to prevent failures (Royal Aeronautical Society, 1991). Many reported expert systems, have been simple to develop, and low in overall costs and yet, it is said, they enhance human expertise and yield significant improvements in efficiency and quality (Lischke and Meyer, 1992)

3.2.6 Rotating machines

ARNETHYST diagnoses problems in rotating machines. Rotating machines, such as pumps, compressors, fans, etc., all produce vibrations as they rotate. These vibrations occur due to imperfections in the bearings, the mounting of the equipment, the shape of the shaft, build-up on the blades, etc. AMETHYST addresses all of these problems using a spectral analysis of the vibration data to determine the nature of the fault. The system is rule-based, employs backward chaining, and was implemented using the shell CRYSTAL. The system runs on an IBM PC. It also communicates to the IRD database, which contains component vibration information. The VIOLET software package is used to access and control database for spectral data storage. The ARNETHYST system was developed at Intelligent Applications Ltd., West Lothian, Scotland, U.K. (Milne, R., 1991)

3.2.7 Concrete dam risk assessment application. An expert system was developed to assist in the field inspection of existing concrete dams for the purpose of risk assessment. The symptoms and failure modes identified by the expert system along with the required knowledge and procedures are organized in a structured knowledge tree. The firing of rules for each consultation traces part of the inference tree containing the structured knowledge. Interaction between nearly decomposable problems are executed with knowledge procedures, shared rule groups, and known values. The system was developed at Minnesota University Minneapolis, M N. (Frank, B.M. and T. Krauthammer, 1988).

3.2.8 Finite element analysis application. An expert system has been developed to assist in finite element (FE) analysis of the deformation stresses in physical structures. In order to design a numerical model of a physical structure, it is necessary to decide the appropriate resolution for modelling each component part. Choosing the appropriate resolution, or finite element mesh, requires considerable expertise. The inductive logic programming algorithm called Golem was used to form PROLOG rules for this mesh generation expert system. (Dolsak, Bojan and Anton Jezernik, 1991)

3.2.9 Line safety code (LSC), reviews architectural designs for conformance with the Line Safety Code of the National Fire Protection Association. The system uses building design information as supplied by a Computer-Aided-Design (CAD) system. LSC stores design information in frames. It reviews this information to make sure the design is consistent with the important fire safety standards. The system integrates frames, rules, and algorithmic procedures. It is implemented in an expert shell call KEE on a standard personal computer, TI Explorer. (Lathrop, J., 1985).

3.2.10 Oil hydraulic circuit-simulator (OHCS) assists engineers with designing hydraulic circuits. OHCS integrates four processes of expert reasoning, designing, analysis, drawing and inspection. The system is able to apply the expertise of the designers to generate circuit

designs and computer-aided-design drawings that meet specifications. The system uses both rules and frames. OHCS runs on a Symbolic LISP machine and is implemented in ART. It was developed at Kayaba Industry Co., Ltd., Kanagawa, Japan. (Nakashima, Y. and T. Baba, 1989.)

3.2.11 Radiographic image NDT diagnosis application. An expert system was developed to assist in the analysis of data from radiographic image non-destructive testing (NDT). The system classifies and evaluates the defect against quality assurance requirements of the inspection process. The system is based on a hierarchical frame-based knowledge representation technique and employs backward chaining. The system also uses certainty factors for inexact reasoning. The system was developed at the University of Surrey, Surrey, UK. (Kehoe, A. and G.A. Parker, 1991.)

3.2.12 Material defect detection application. An expert system was developed that detects and categorizes defects in digitized images of materials characterized by complex texture patterns. The system performs two major tasks: image segmentation and defect classification. Segmentation is done in two steps. First, individual texture samples are isolated. Second, a pyramid linking scheme is used to locate defects in each sample. This pyramid linking scheme can be fine-tuned to various textures and to the size of the defects to be detected. The defect classification method is dependent on the material being analysed. The system was developed using a hierarchical defect classification scheme for analysing wood. The hierarchy incorporates shape descriptors, size, and textural descriptors of individual defects. The system was developed at the University of Tennessee, Knoxville, TN. (Brzakovic, D., et al., 1990).

3.2.13 Information Management BROWSER heuristically searches a database containing information on U.S. Navy aircraft with little or no human intervention. The formation of databases containing information on mechanical systems for troubleshooting purposes has become increasingly popular and important. Examination of these databases by humans can be very costly, and labour intensive. BROWSER searches the database guided by models and heuristics looking for interesting patterns or configurations. The user is then notified of the existence of these patterns. The system is implemented in LISP on a DEC mainframe. It was developed at the University of Illinois at Urbana-Champaign. (Dankel, D.D., 1979.)

3.2.14 CPMAPS II, Computer Programmed Manufacturing and Assembly Planning System, assists in the manufacturing of printed circuit boards (PCBs) at Northern Telecom Canada Ltd. The system uses a hierarchical design approach based on two levels. At the first level, the design and engineering constraints applicable to PCBs are considered. At the second level, workplace constraints and capabilities that affect the plan are considered. The system

interacts with manufacturing databases and determines process plants to assemble through-hold and surface-mount electronic components of the board. The system is frame based, was implemented using KEE on a SUN 3 work-station, and was developed at Northern Telecom Canada Ltd.
(Dagnino, A., 1991).

3.2.15 GREASE aids in the selection or design of lubrication products that extend the life of machines used in a manufacturing process. It can also improve the quality of the material being manufactured. The goal of GREASE is to find the best trade-off between the price of the lubrication product and the amount that it extends the life of the manufacturing machine. In addition, several other constraints on the lubrication product may be imposed by the raw material being used in the manufacturing process, the manufacturing operation, and by the operators of the machines. GREASE was developed at the Intelligent Systems Laboratory of Carnegie-Mellon University, in cooperation with Gulf Oil. (Fox, M., P., 1985.)

3.2.16 RBEST: An expert system for disk drive failure diagnosis during manufacturing. It determines the cause of failure in disk drives during their final 24 hour environmental stress test at the end of the manufacturing process. It uses rule-based reasoning techniques with a modest 130 rules, which distinguish between just under 100 different rectification procedures It has been used since the end of 1986 and has helped the manufacture, Hewlett-Packard, in allowing a 20-fold increase in production rate of disk drives. Within four years, Hewlett-Packard estimated it saved at least two million dollars in direct labour savings alone, for a total cost of 150 thousand dollars. Hewlett-Packard stated the main reasons for the success in the RBEST system was as follows:-

1. the choice of a problem whose solution is of real economic valve.
2. The use of controlled incremental phototyping.
3. Strong support from immediate management.
4. The use of 'conservative' artificial intelligence and expert system technology: structured selection by simple pattern-matching, and no use of uncertainty-restrictions which were appropriate to the chosen problem.

As well as being a success in itself, it has verified the success possible form expert system and allowed the development of further systems at Hewlett-Packard. (Braunwalder & Zaba, 1990)

Braunwalder, K. & Zaba, S., "RBEST: An expert system for disk failure diagnosis during manufacturing" in "Practical experience in building expert systems", Ed. Bramer, M.A., Publ. John Wiley & Son Ltd. 1990.

3.2.16 Summary of domain-based expert systems

In domain-based failure analysis expert systems, it is important to know not only the different modes of failure and their relationship to each other, but also the different levels (heuristic, qualitative, and quantitative) of understanding that are required to find a solution. All this knowledge can only be developed through a detailed survey of causes, effects, solutions and examining the problems in a holistic manner (Thomas, Graham-Jones, Mellor, 1994). This survey can be extremely difficult to produce. However, if the knowledge is readily known, which generally means that its domain is limited in scope (bearings, disk drives), then a successful expert system is highly likely. Having a well known domain is the main advantage in the success of domain based expert systems. Direct cost saving for these systems can be high, however the indirect cost savings, though difficult to assess, can be far greater.

3.3 Design expert systems

Many component design expert systems have been developed. They are generally very specialised to an industry and have been developed by a company or in a joint venture between a company and a university. Examples of these are:- "FRAES" an expert system that assists in the design of flexible risers in the offshore oil industry (Geymayr and Ebecken, 1991) (A flexible riser is a high pressure flexible pipe in either a static or dynamic application to bring oil and gas from well to the surface); a knowledge-based system for centrifugal fan blade design (Chon, Kim and Kim, 1993); and a knowledge-based system for mechanical spring selection during preliminary design (Dentsoras and Maurommatis, 1993). These systems are limited and can only tackle the problems for which they were designed.

3.3.1 Failure mode effect analysis (FMEA) expert system

This is an extremely complex problem. Therefore a conceptual model of the Failure mode Effect Analysis FMEA process has been developed in an attempt to automate the FMEA process, and to further research on FMEA (Russomanno et al 1992). Other researchers have developed a tool that automates the reasoning portion of a FMEA. This is being adapted for various computer-aided design and engineering (CAD/CAE) platforms (Bell et al, 1992).

3.3.2 Case-based reasoning design expert systems

In many cases in design and failure analysis the problems could be apparently completely new to the expert and the computer system. Case-Based Reasoning uses previous experiences to solve new problems (Kolodner, 1985) (Graham-Jones and Mellor, 1994). CADET (Sycara et al, 1992) is a good example of a case-based designer's assistant for mechanical design. CADET retrieves and reuses previously successful designs while avoiding previous failures such as inadequate materials, exorbitant expenditure, and excessive stress loading. Design case retrieval is what a human generally does when undertaking a new design, so this method is not only a great help for designers, but also to the failure analysis engineer, because past failure cases can be stored.

3.4 Mechanical type failure analysis systems

When a failure mechanism is the domain of the expert system, then the systems tend to be based around predicting failure rather than analysing failures. Examples are detailed below.

3.4.1 Fatigue failure analysis expert systems

Of the different software applications related to fatigue, many were developed for companies or by universities for research. The functions they perform may be classified as follows:- (i)General purpose with all the following or single packages for (ii) Fatigue design; (iii) Fatigue Life Prediction; and (iv) Database retrieval, (Kawamo, 1990) (Shuto, 1990). Typical examples are as follows:-

An expert system for fatigue testing of airframes (Gubarev, 1991) was designed to identify failure situations before they occur and change parameters to prevent a systems failure. An expert system was used because full scale airframes include a complex variety of experimental equipment that is highly automated and processes large amounts of data. Analysing the data in conditions of time shortage can lead to erroneous decisions, which can overload the structure or lead to unintentional destruction or standstill of the rig.

A knowledge-based system for the assessment of component fatigue life and for advice on changes in design to modify fatigue life was developed at Bristol University, U.K. (McMahon et al, 1990) (Brown, 1991) The KBS developed was in two parts, Fatigue Life Assessment Expert (FLAE) and Fatigue Life Modification Expert (FLME). The FLAE objective was to predict, for a given component geometry, material, and loading, where component failure would occur and the fatigue life. The FLME's object was to advise on the effect of design modifications such as alternate geometry, materials, surface condition, or cold working, on fatigue life improvement. The difference between this system and other systems is that it reasoned using the geometry of a component to find values for stress concentration factors (K_t), rather than the user looking-up such values in selected texts such as Peterson (1974), and

ESDU (1982). The system performed its design task, but could only work with the limited number of geometries in the knowledge base.

3.5 Corrosion failure analysis expert systems

Many expert systems in the corrosion field (Roberge,1994) are based around quantitative reasoning (Corrosion calculations) and have been developed for design rather than failure analysis, but nevertheless are still of use in failure analysis.

3.5.1 Corrosion expert systems built around standards

Good examples have been developed by the NACE International (National Association of Corrosion Engineers), of which a number are computerized technical reports and standards. A few examples are:- MIC.AB is a reference library of 280 citations on microbiological influenced corrosion, created by NACE technical committee T-3J-8. PC.MRO175 is a hypertext format blended with a rule-based expert advisor for the NACE standard on sulphide stress cracking resistant metallic materials for oil field equipment, (MRO175). PETRO.COR1 is a materials' selector for sucker rod pumps based on NACE and API standards. There are many more knowledge-based systems available through NACE Publications.

3.5.2 Crevice corrosion engineering guide

Developed by the Nickel Development Institute (1994) and available at no cost. Based on a mathematical model of the corrosion process, it allows the user to determine which grade of stainless steel is best able to resist crevice corrosion in a given aqueous environment. The user selects the environmental variables such as water chemistry, temperature, scaling tendency and pH level, as would be found in power, pulp and paper, desalination, marine, and water treatment industries. Apart from being a useful expert system, it also promotes the use of Stainless Steel, which in turn promotes the use of Nickel a constituent in the majority of Stainless Steels.

3.5.3 Stress-corrosion cracking expert system (SCHIST)

The expert system works in a similar manner to the Prospector (Duda, Gaschning and Hart, 1977) i.e. a plausible-inference type expert system, but a lot simpler and was constructed with the two objects of investigating computer techniques that might be suitable for the materials engineering field and if so, then being a prototype system. Its function is to predict the risk of stress-corrosion cracking in stainless steel. Stress-corrosion cracking occurs due to the actions of stress considerably lower than that required for yield and a corrosive medium. Its occurrence is difficult to predict and expensive. The factors relating to SCC are very complicated because of the uncertainty in predicting the nature and magnitude of the factors. Thus an expert system was used to calculate the risk of different factors in SCC, such as temperature of the corrosive medium and whether there are any crevices in the surface. The

knowledge base of rules and facts specific to the SCC was built by two corrosion engineers and contains a mixture of 'rule of thumb' rules from experience and well known physical, chemical mechanisms.

3.5.4 Cathodic protection diagnostic expert system

A knowledge-based diagnostic system called CP Diagnostic was developed for trouble shooting sacrificial and impressed current cathodic protection systems. It works in conjunction with the CP Diagnostic database system, which stores inventory and field measurement information for the CP system and flags problem areas. When a malfunction is detected, the expert system queries the user and the companion inventory and field measurement database to determine its symptoms. (Van Blaricum et al., 1994)

3.5.5 Multimedia corrosion knowledge-based systems

Roberge (1994) gives a literature review of corrosion knowledge-based systems. The next stage of development for corrosion knowledge-based systems is improving the user interfaces using multimedia techniques. A good example of this is where a computer corrosion model based on polarization curves, was developed by Trethewey et al., (Trethewey and Keenan, 1992). This is a DOS based calculating application. This has been added to and developed using multimedia techniques to produce "The Corrosion Manager" (Trethewey and Keenan, 1994). It has a mixture of calculating modules and textual information (corrosion theory, cases, failure analysis and experiments) taken from published works (Trethewey and Chamberlain, 1988, 1996). The "Corrosion Manager" (Trethewey and Keenan, 1994) is under continuous development and with its planned reasoning module, will provide an excellent expert system, that gives answers to real problems.

Another multimedia corrosion system, different from the above by being a knowledge-based system with little intelligence, based more on published reference books, is the "Active Library on Corrosion". (Bogaerts and Agema, 1992). This is a good CD-ROM reference package for corrosion in general but not an expert system. The intelligence is built around a cube of factors, Failure mode, Materials, and Environment. The users select from lists, and this leads them on via keywords to published documents.

3.6 Materials selection.

There are many materials' selection tools available (Waterman et al, 1992), but the most advanced selection tool is the **Cambridge Materials Selector** (CMS) Ashby et al, 1995a & 1995b). The selection methodology used, relies on materials selection charts which display material properties (or groups of properties), and selection criteria (of which "performance indices" are the most powerful) which isolate the section of a chart containing the materials

required. A material selector is useful in failure analysis to check that the initial design is adequate for the applied end use

Another application is the **Computerised Material and Process Selection tools** for students and engineers. These two packages were developed at Bournemouth University in the context of the Department of Product Design and Manufacture's interests in the application of 'concurrent engineering philosophy to product design. There objective was to provide early advice on material and process selection to designers who were not experts in these fields. They found that the majority of commercially available packages seem to have been developed for metallurgist or material scientist, rather then designers. The programs were developed for use on PC-based systems and with non-graphical but user-guiding interfaces. It was developed using the Crystal expert system shell, which is a simple rule-based system. Although very limited and difficult to up-grade, the programs performed satisfactorily. As in many expert systems they found difficulty in finding non-conflicting information even with basic property values in which the ranges were subject to argument.

In addition to being a design tool, the development was also made to produce educational tools for design and engineering students which not only assist them with the material and process selection but take the student through the logical considerations and steps involved in material and process selection (Kokotos, T., Tabeshfar, K., Wilson, A., 1994).

3.7 Other AI fields used in failure analysis

Apart from ESs and KBS, which are the main fields of interest of failure analysis. Other AI fields are of growing interest and are being developed into systems which could aid failure analysis, such as pattern recognition, neural networks, fuzzy logic, natural language processing. Example are as follows:-

Pattern recognition

A pattern-recognition-based expert system for fault diagnosis in a liquid rocket engine. Using the system's knowledge about the different nominal states of the engine represented as generalised patterns, the detection and diagnosis task can be seen as a comparison of the current rocket engine data with the nominal pattern. A decision about failures occurring could be derived very quickly if there are unacceptable deviations. (Matijevic, Zeljko, 1992)

Neural networks

An artificial neural network developed to represent fatigue crack growth and the cyclic relationship of different loading spectrums. Using flight and experimental data for crack growth verses cycles as inputs, the trained network is able to generalise and represent the crack growth behaviour for arbitrary loadings (Pidaparti, R.M.V.; Palakal, M., 1993).

Fuzzy logic

Many types of uncertainty exists in the behaviour of metal fatigue. Often insufficient and/or imprecise information must be used. A model has been developed to use the information available as a fuzzy set to evaluate the fatigue condition of welded defects and discontinuities. (Bowman, M.; Nordmark, G.E.; Yao, J.T.P.,1987)

Natural language processing (voice & text recognition)

Voice recognition involves the input of the spoken voice being turn into text (Green, T., 1995). Natural text language involves understanding the context of a written statement. This allows for poor English grammar and poor spelling to be understood. Although, presently there are no reported use of voice recognition in failure analysis, there are many within the medical field, especially coroners who need to take notes during body examinations. This system has been developed by Phillips Electronics. In addition to Phillips who produced a professional system directed at a profession, IBM and Dragon have produced programs which through voice commands controls the personal computer and translates continous voice to text. This advance is made possible by the increase in processing power in cheap personal computers. It would be quite possible for a failure analysis consultant to use such a system when on site in which to collect written transcripts. As for text recognition, the present expert system developed by the author uses natural (text) language recognition and cased-based reasoning.

3.8 Conclusion

Within this thesis "expert system" is used as a broad term to cover expert systems, knowledge based systems and model based systems. Although there are difference between these as previously detailed, expert systems cover many reasoning methodologies and extend beyond simple rule based system to embody more complex representations of human knowledge, for example case based reasoning and hybrid reasoning methodologies.

There are many different expert systems which have been developed. A simple search of the literature will show a plethora of expert and knowledge based systems based around diagnostics. However the majority of the literature typically focuses on either technical details described using jargon or the financial benefits to its development. The technical descriptions are more of a marketing exercise for the expert system and its development organization. Such accounts, technical or financial, are of little value to the person who wish to develop their own expert system or would wishes to gain a practical understanding of expert system development. Therefore, many of the expert systems which could have been discussed have been left out of the discussion. However the aim of the expert and knowledge based systems discussed above is to show the breadth and variety of systems that have been developed and

to bring together the practical experience that could be used in producing future generic expert system for failure analysis.

The field of developing expert systems is currently characterized by a wide range of theoretical viewpoints, but an absence of generally accepted theory in many important areas prevails. Opinions on the commercial value of expert systems vary from the extremely negative "Expert systems have failed" through to the dismissively positive "Expert systems are now routine in commercial applications". Although there is now a growing collection of work related to expert system, there is a shortage of hard information both within the expert system field and the domain field. This is not helped by the widely varying definitions that seem to apply. Much of this is historical and relates to a research group's promotion of particular preferred terms. For example, the majority of expert systems use rule based reasoning, and yet within the literature many other terms are used to promote these research or commercial programme. for example, plausible-inference type expert system, a structured knowledge tree, and IF-Then rules.

The different expert systems described above are in a sense completed in that they are working technically. This however does not mean they are successful in a practical or commercial environment. The majority of expert systems are under constant improvement. The improvements could either be in the software tools used or in the development of the knowledge acquisition and representation. The knowledge within this subject field is so extensive that it could be considered limitless, which means information relevant to all failures in every system in the world could be entered. Although in the future, collecting together this information might be possible, without the formalized structures developed in this and other expert systems, such an exercise would be futile. At present it is economically impossible to collect together and maintain every bit of information relating to all failures. So, apart from the development of a formulised model for the knowledge, it is important to know how much information is actually required by the expert system to function. This is covered later in the thesis, and is based on a survey where the possible users were asked their opinions (Chapter 16).

Thus to develop successful expert systems it is important to identify the underlying principles behind the successful and the not so successful This can be achived by the potential developer asking the question: "If I am starting or considering an expert system project today, What should I know that will help me? What principles have emerged in the last five years that will stop me from having to reinvent the wheel myself? What are the key factors that will determine whether or not I will succeed".

The majority of successful expert systems have worked because their scope was limited and focused on a single domain of knowledge. When it comes to developing a generic failure analysis system, this is far more complex.

It is most likely that the majority of the expert systems discussed are out of date. So how do they help present failure problems and the development of further expert systems? One advantage is that they have been heavily tested and revised and, although the software frame might be based on old techniques or old programming tools, the knowledge structure can be transferred on to newer systems. Thus when designing a new system methods to combine old data together with methods to update to newer system to come must be taken in to consideration.

The difficulty in transferring this knowledge, is based on the software and the structure of the knowledge held within the expert system. Many of the older systems used a rule-based system. If these rule are written in plain english then knowledge transferal is easy. However, if the rules are embedded with in the program then knowledge transferal is very difficult and in some cases impossible. However, if the knowledge could be copied, then there is the problems associated with copy-right legislation and the relevance of the information to generic failure analysis. In examining the different expert systems above the majority of data is either non-transferable or not relevant, the rest which generally means newer data, are copy-right protected. What can be learnt from the different expert system is as follows:-

1. The majority of systems were based on rule-base reasoning, although case-based reasoning is a recent development which shows great promise.
2. Successful expert systems were due to a small-manageable domain.
3. There is no generic failure analysis expert system.

Chapter 4 Issues involved in failure and failure analysis methodologies

4.0 Introduction

The purpose of this chapter is to understand what people consider failures to be and examines people's preconceived ideas and how people undertake failure analysis. It also considers how all the information gained in an investigation affects the development of a failure analysis expert system and thus the ability of the expert system to aid an investigation.

4.1 What is understood by the term "failure"?

Even with all the advances in technology and the understanding of science, failures are still deemed to have occurred. In reading a newspaper, headlines such as the governments failure to do this or that, financial failure, and catastrophic air crash, can be seen splashed across the front page. Are these failures? These have been considered a failure to at least one person, such as the journalist who wrote the article. Yet what is it that makes them a failure? This might be considered a stupid question to ask because people assume that they know intrinsically what constitutes a failure.

Dictionaries define failure variously from: " the condition or fact of not achieving the desired end result" or "the condition or fact of being insufficient or lacking" or "nonperformance of what is requested or expected" to more human associated meanings. For example "an unsuccessful or generally ineffective person", (Reader's Digest, 1994, p550). This illustrates the multiple meanings and thus the confusion in the meaning of the word 'failure'.

In the author's opinion, most would consider a failure to have occurred if disappointment arises because of an assessment of an outcome from an activity. A major accident to an airliner is considered a failure by all concerned, unless the loss was due to a terrorist bomb, where it would then be considered a success by the terrorist and some of their followers, if that was their desired outcome. Others would consider that the failure occurred due to lack of airport controls and the inability of the aircraft to withstand the explosion. Thus the assessment of an outcome as a failure is dependent on the values held by those making the judgement. These values affect how much of the performance of an activity or component is included within the assessment. For example, if a shop-sign starts to discolour then this is considered a failure, whereas if a ballast tank of a supertanker discolours and corrodes, this is not considered a failure till there is at least a reduction in thickness of 25%. This percentage is purely based on the judgement of the Classification Societies and their understanding of what would constitute failure. Another example from the Engineering Materials Consultancy Service case histories was a dentist's chair which had very slight corrosion that in most cases would be considered satisfactory. However, the staining and unslightly visual marking was detremental to the image of a clean and germ free environment. Hence this small amount of

corrosion was considered a failure. Thus the level of corrosion constituting a failure is different for the three components. What quantities or qualities are regarded as significant, and what standards are adopted, vary from individual to individual, and from group to group. They are also liable to change with time and the occasion of the judgement and the viewpoint taken.

So how is an expert system able to assess what would be considered an engineering failure or not? In the author's opinion, a failure of an engineering component is said to have occurred when it does not perform its required function to its required design standard. Thus an internal combustion engine might still work firing on one less cylinder, but it would be considered a failure because the required design standard is to run with all cylinders firing in the correct order. If a failure has occurred then an expert system could make some judgement. However to predict when and what mode of failure is going to occur in the future is a lot more complex and a different approach is required This needs a holistic systems approach and this will be discussed later in section 4.6(1)

Thus times of failure and time to failure (service life) are important factors in assessing failures and these times change with advances in technology. For example a car built in 1940, which was designed to be as reliable as possible, might drive for 1000 miles without a break down and this would be considered as a success. Today, however, if a car broke down after 12,000 miles then it would be considered a failure.

Within the media, the word catastrophe is deeply associated with all failures. The articles generally cover the unexpected and overwhelming nature of the failure, whether it is an air crash, a financial crash, or some natural disaster. These failures should be associated with our inability to cope with their effects and in predicting then. If a failure is predicted, planned for and the effects can be coped with, then a failure might not actually occur or it might be described as a minor failure with little effect. (Bignell & Fortune, 1984 pp6)

Apart from catastrophic and minor, failures can also be described as overwhelming or partial, and sudden or slow (Bignell & Fortune, 1984, pp7). For example there might be an overwhelming fracture in a structure which causes its collapse or there might be a small fracture at a stress concentration. Alternatively the fracture might be a sudden brittle fracture or a slow growing fatigue crack. It is the understanding of these issues that helps the knowledge engineer assimilate the knowledge to build an expert system.

The term "bad luck" is not a helpful term to describe failure as it would indicate an element of chance. Although this is true up to a point, to explain failure as a chance happening suggests that we have little effect on the outcome (Bignell & Fortune, 1984). For example if an

inspector of an airframe misses a large fatigue crack, that is poor inspection rather than bad luck. However, inspection is not always easy. With some structures, inspection can be extremely difficult; for example the welds inside a ship's hull. Also, the failure could be the product of many processes and interactions. Failures are multi-causal with multiple outcomes and due to a complex interaction of causes, processes, and outcomes, finding a simple linear model for a failure situation is very rare. It is within failure analysis that these interactions are assessed for their contribution towards the main cause of failure.

A human expert can examine many interactions simultaneously. Computers are classically linear in their analysis of situations. This paradox is an obstacle to the development of an expert system for failure analysis. This is taken up later in chapter 7. It shows how a systems approach built up from a deep understanding of the different modes of failure and understanding how an expert would go about analysing different failures are solutions to this paradox.

4.2 Human error associated with failure

When describing the cause of a failure, human error is freely discussed as the cause for failure. In the last century the chief engineer was regarded as responsible for all that was done or not done by those under him. Thus Sir Thomas Bouch, the engineer for the ill fated first Tay bridge in Scotland was held by the inquiry to be "principally, and to some degree entirely responsible" when due to bad design, construction and maintenance; the bridge fell into the Tay estuary (Prebble, 1975, p213). However humans have an effect at all stages of the product life cycle, whether this is at the procurement, design, manufacture or end-use stage. Trethewey et al (1994) has described the different contributions made by people to the risk of failure of engineering systems by corrosion. He states "While designers have considerable responsibility for the economic and effective creation of engineering systems, they cannot be held responsible when either the manufacturer, for reason of economy, uses different materials from those specified or the user fails to maintain proper control over the environments in which the system operates. Indeed, one responsibility of the professional engineer is to control the interaction between people and systems by means of operating and maintenance schedules." A summary of his work is given in the table 4.1. However, the functions have been edited to include all generic failure cases.

Person	Functions
Procurer	Specification and compatibility of system (e.g. materials, services, environment and personnel); Control of budget.
Designer	Geometric shape and structure; Choice of materials; Operational environment; Choice of protective and preventive methods;
Manufacturer	Accurate reproduction of design; Use of specified materials, services environment and personnel; Use of correct processes (heat treatments, fabrication technique, coatings); Correct application of protective and preventive measures; Correct monitoring of the environment during storage and transportation.
User	Correct operating, monitoring, and maintenance procedures; Use of the correct materials and specifications to replace failed, or worn parts;

Table 4.1

What Trethewey said above is true; however the designer should assume that the manufacturer will do something not to standard, and the manufacturer has to consider that the design might be wrong for a manufacturing situation. Also both the designer and the manufacturer have to assume error in what the procurer does and how the end-user treats the product.

Today, the responsibility is with everyone. Everyone has to be sure that throughout the life cycle of a product (system) the correct specification and the correct application of materials, services, processes, environment and personnel, are used. Inadequacy at any stage will result in an increased propensity for failure.

Occasionally there is room for dispute about human responsibility, such as when some new effect in technology or science emerges because of an investigation of a failure. It would then be up to the legal system to judge responsibility. However whatever their decision, and although difficult to prove, it could be argued that all failures can be traced back to some form of human error. The Comet aircraft crashes are an example. The cause of failure was due to fatigue crack originating at the stress concentration associated with the corner of the windows (Ross, pp332, 1995). This was the primary mechanism for failure. Nobody was held responsible because it was argued that it was not expected that standards need be set up and met with respect to unknown phenomena. Yet fully representative testing that simulated real

life service conditions was only carried out after three Comet aircraft had crashed. This was the human error, but this type of testing was not considered important until three aircraft had crashed. In the author's opinion, this and many other failures can be attributed to the lack of available information at all levels in the system's structure. If the engineers had a readily available source of information that told them the importance of testing, stress concentration, and fatigue, this failure might not have occurred. This is where the developments of knowledge and expert systems for failure analysis are best suited. However it is unlikely that an expert system will conclude that failure was due to some form of human error (the secondary mechanism and generally the root cause) but rather to a primary mechanism or failure mode, for example corrosion, fatigue, overload, etc.

Thus an expert system needs to analyse which failure modes and mechanisms have occurred, before any understanding as to the root cause of failure can be traced. The development of an expert system that goes beyond diagnosing failure modes and mechanisms, and diagnoses the root human error is at present still at the research stage. This is being attempted by Trethewey (1997), by using a holistic systems approach, which promises advances in failure diagnostics.

4.3 What constitutes a failure mode and a failure mechanism?

A failure has been described by the author to have occurred if disappointment arises because of an assessment of an outcome from an activity. This definition covers all failures, but in some respect this definition is too complex. A simpler definition for failure is "the inability of an item to perform its designed task" This relates more to engineering failure and consequently one might define a failure mode as the process that affects an item's ability to perform its design task. This definition reflects an item's ability to have a failure mode without the item's performance being affected. For example a component could be corroded, however it could still perform its required function.

In developing a formalized system for failure analysis, the different categories of failure have to be distinguished, and thus they are split into failure modes and failure mechanisms. This has to be done in a standardised manner, understood by all concerned. A failure mode is the physical process or processes that take place or combine their effects to produce failure (Collins, 1993, pp11).There are seven main commonly occurring modes of failure to which all others can be associated. These are Fracture, Deformation, Creep, Wear and Erosion, Fatigue, Surface Damage, and Corrosion (Trethewey et al, 1996).

Each of these has several subsets, these are called failure mechanisms. A failure mechanism is the actual physical, mechanical, or chemical process that produces a particular failure mode. Thus, for a given failure mode there maybe several different failure mechanisms associated with it. For example, thermal fatigue, surface fatigue, impact fatigue, are all

different failure mechanisms of the failure mode 'fatigue'. Other fatigue failure mechanisms include, bending, high and low cycle, corrosion, and fretting. Another example is where galvanic, stress, and crevice are mechanisms of the failure mode corrosion. Fracture includes impact and shock loading failure mechanisms, and surface damage includes embrittlement from physical and chemical interactions. Each is similar in nature in that it causes damage to materials. This damage could either be surface, subsurface, fracture into two or many pieces. However, the different mechanisms have a very different initial cause.

In structuring the knowledge for the expert system, some confusion exists when considering a failure mechanism that is either a combination of mechanisms (Stress corrosion cracking) or the combination of two failure modes (corrosion fatigue or creep fatigue). To consider these combinations as separate failure modes is wrong and difficult to link within any expert system. However if they are considered as failure mechanisms which are a part of the two different failure modes then the correct links and references can be made. A good example is corrosion fatigue, because the synergistic effect of the two failure modes makes the severity of the final combined failure mode more. For example corrosion fatigue on a rivetted lap joint is considerably more damaging that corrosion or bending fatigue alone. An expert system, ideally has to consider the increased severity of the failure situation Also if a user is browsing information, they need to see all the links possible. This would not work if they are separated but works well if they are linked together by (software) knowledge associations (Links) to any relevant information such as failure case histories, remedial actions and solutions, associated questions and rules used in failure diagnosis, i.e. virtually anything related to a given failure mode.

4.4 Methodologies for conducting failure analysis

When designing an expert system understanding fully the task that the system is to aid or perform is important. Thus, in developing an expert system for failure analysis, understanding the ideal generic methodology involved in failure analysis is important.

In investigating the different methodologies for failure analysis, it was surprising to discover just how little had been written. There is a considerable amount of information as to the different causes, sources and effects of failure, but little on how to undertake an investigation. It seem to be assumed that if an engineer is given the different methods by which components fail, they are able to discover the root causes. One reason why there is little information as to the correct and ideal methodology for failure analysis, has been suggested by R.C. Anderson, (1986). He states *" Failure analysis is like playing detective with inanimate objects. Due to complexity, the following (analysis) sequence is merely a suggestion and a guideline to follow"*. Although, considered correct, for the development of an expert system a more systematic approach is required. This does not seem to be available although, several

researchers have published in this area (G.F. Van der Voort, 1975) (K.Reynolds, 1991) (R.C. Anderson, Metals Handbook, ASTM, pp32.1-32.2). Although somewhat dated, the sources are still relevant, and a generic methodology for failure analysis has been complied below using these published works and the authors own experience both from within the consultancy field and following detailed discussions with the other failure analysis consultants listed in Chapter 5 Section 5.1(iii).

The objective of an investigation will affect the possible sequence of analysis. A failure investigation can have the following objectives (Ross, 1995, pp4):-

(I) To affix blame in lieu of litigation, or compensation between any person or organisation associated with the component or product (i.e. suppliers, users, manufacturers, designer, repairers, etc.)

(ii) To affix blame to an internal or external organisations or personnel, and thus to stop the recurrence of the failure mode. This is typically undertaken by government appointed organisations, where there has been considerable loss in either lives or financial value. Typical examples are the Comet aircraft investigations, the Piper-Alpha oil rig disaster, or the NASA shuttle explosion.

(iii) Fundamental investigation to stop the recurrence of that particular failure mode in a product. This is typically undertaken in-house, i.e. within a company for their sole use to improve their product quality.

(iv) For a purely academic investigation that presently has little commercial relevance.

Different investigation objectives will require different levels of control.Control within a failure analysis sequence means the control of procedures, and in the accurate and detailed account of the sequence of analysis together with the findings from the analysis. If the investigation is to affix blame in lieu of litigation, then the highest level of control is required, whereas a purely academic investigation could have the lowest level of control. The other levels of control are as listed in the order given above. Whatever the objective, some failures are "routine" and may not always require a highly controlled and detailed failure investigation to be effective in preventing further failures. Whatever type of investigation is undertaken, improvement to the product quality can be achieved. Whether these improvements are implemented is an economic consideration.

Unfortunately, both industry and academia have generally failed to put sufficient emphasis on the need to develop and encourage the science of failure investigation and the dissemination of the resultant information. In many situations, investigations are carried out, but the manufacturer concerned may not wish to share the resulting information publicly. At other times, there is probably no reluctance to share such information, but reporting channels are

inadequate for making such information available to those who could benefit and in turn, provide feed back. Finally even within a given organisation, failure analysis data and conclusions may not be adequately communicated. This might mean that the designers do not implement design changes aimed at developing an improved product, or the operations personnel do not eliminate processing problems and improve quality control.

The method in which a failure analysis is undertaken relates to the individual and there are as many methods as there are individuals. Thankfully, two individuals might use two different methods but come up with the same conclusion. However this is not always the case, as an individual's background and personality may lead to different conclusions. It can be said that given one failure problem, two failure analysis investigators, may arrive at three very valid reason and solutions. Thus, a failure could be misinterpreted and remedial actions could, in the best case scenario, have no ill effect or in the worst case lead to further catastrophic failures and deaths. A classical example of this is the Flixbrough disaster, where a pipe was installed incorrectly to cover a minor failure, but inadvertently caused the destruction of the plant and the loss of lives. Another example is where a mechanical or civil engineer pays more attention to the stress loading than a material scientist and vice versa. Similar imbalances in approach may occur when other specialists conduct a failure investigation, since few specialists would be fully knowledgeable in all fields of failure investigation and the interacting disciplines that can be involved. Thus, a team effort using different specialists is usually the best approach. However, apart from large scale failures such as those dealt by litigation or government inquires, such teams cannot be afforded. The majority of failures are those which involve minor problems and are thus seen as minor. But it is the accumulation of these problems which can in the long term carry the greatest cost. The use of a computerised decision support system to act as the team of specialists is thus seen as a great asset in investigations. However unless the computer system, expert system, knowledge based system or whatever, can fit into the generic failure analysis procedure, it is unlikely to either be used or be of any help to the engineer undertaking the analysis.

It may be asked if there are set stages in undertaking failure analysis. Apart from the basic steps of examining the evidence, collating the appropriate information and formulating preliminary conclusions, there are as many way as there are investigations. Most investigations will not involve clear-cut steps. If the probable cause of a failure is apparent early in the investigation, the pattern and extent of subsequent investigations (tests, examining the literature, etc.) will be directed towards confirmation of the probable cause and eliminating other possibilities. (Metals Handbook pp31, 1986). Other investigations follow steps that were previously used by either the failure investigator, the company standard, or the investigator's manager, whether ideal or not. As new information is assimilated, changes in the direction of the investigation proceed and new reasons for failure develop.

If the investigators have an extensive budget and extensive laboratory facilities, they may wish to undertake all possible tests. In litigation, this may be required, however for the majority of cases, a careful evaluation of the case and any background information may show that the majority of tests are unnecessary. So where is the split between required and unnecessary tests? In the author's experience many tests undertaken during an investigation are, with hindsight, unnecessary for the actual diagnosis. However, they are useful, to either dismiss other failure causes, to gather information with which to provide a remedial solution to reduce the propensity for failure recurrence, or to educate the investigator in better failure investigations.

It is important not to curtail the investigator from undertaking such work, but it must be born in mind that a better analysis of the effect people have on the possible failure could reduce the number of tests required.

4.5 The which, why, what of failure investigations

By understanding the basic structure of a failure investigation, clear guidelines can be given as to the structure, scope, and possible performance of an expert system. A failure investigation can be split into three sections:-

(1) Which failure mechanism occurred?

(2) Why did that particular failure mechanisms occur and not another?

(3) What remedial actions can be undertaken to reduce the propensity for failure.

The "Which" is very different from the "Why". Knowing which failure mechanism occurred generally involves visual, macro and non-destructive testing, whereas knowing why a particular failure mechanism occurred could involve destructive testing or non-repeatable work (Ross, 1995, pp6). For example, if it were asked how a bolt fractured in two pieces, with a smooth, flat surface with a few beach marks visible failed, the majority of investigators would diagnose a fatigue type fracture. However, if it were asked why did it failed by fatigue, then information is being asked which is external to the bolt, for example, what torque settings did the operator use, what components are joined together by the bolt. It is quite clear that finding how a failure occurred is much easier and requires less complex information than finding why a failure occurred, which involves many external influences including people.

Thus within an expert system it is likely that only the "How" part and not the "Why" part will be implemented into a successful expert system, although, it would be extremely useful to include the "Why" part in future developments if at all possible.

If an expert system can only diagnose the failure mechanism, will it actually be useful to the failure investigator? Although, an expert system is limited, its ability to store information

surpasses any human and thus the information it does supply, i.e. what failure mechanism occurred, will aid the failure investigator in understanding why the failure occurred with that particular failure mode. The expert system is being used to supplement the expert's own knowledge to increase the reliability of an investigators decisions.

4.6 Standard steps in failure analysis

On examining different referenced sources (Collins, 1993)(Ross, 1995)(Reynolds, 1991)(Ryder et al, 1986) and the author's experience, standard methodologies on how to undertake failure analysis can be devised.

4.6.1 Define the failure problem. This is probably the most important stage in an investigation because it defines the investigation path. There is no point in undertaking a massive investigation in the hope that some part of it will be useful. Thus by taking a step back and examining the whole problem in a holistical manner, such as by identifying associated problems, for example, noises, poor performance, smoke, unscheduled stopping of moving parts, fractures, or discolouration, etc., it is then possible to arrive at some conclusions. This includes examining what effect people had on the failure. This is what could be called a holistic systems approach because the whole system is being examined. For example, for the fatigued bolt discussed above in section 3.5, investigations could be focused on the bolt and the failure mechanism would be discovered. However, if the investigation was focused on the whole system such as the location, examining for other external failures, the service history, a better understanding could lead to the actual reason "Why" this bolt failed such as poor maintenance, poor manufacture leading to over-load, etc. This first step back is difficult to model within an expert system. However, the information that this step provides is extremely important to an accurate diagnosis using an expert system. Therefore ideally in future expert system development, this needs to be considered

4.6.2 The collection of selected background information. From the first step detailed above, conclusions can be made as to the amount, source, and what background information to collect. There is little point in collecting vast amounts of irrelevant background information. Typical background information consists of service history including maintenance records and service conditions (environment, etc.). This could also involve discussions with personnel associated with the failure. From there a decision about which areas are to have further detailed analysis has to be taken. This will depend on the investigation, as a super tanker will require a different approach to a failed bolt. A good description on collecting background information in given in Ryder et al, (1986), which covers aspects such as service history, photographic records, selection of samples, examining abnormal conditions, wreckage analysis. Although at the time of taking a photograph or sample its location might seem obvious, however, as some failure investigations might

continue for years and different investigator might examine this evidence it must be stressed how important it is to record all the information in a traceable manner, i.e. if a photograph is taken where was it in relationship to everything else. This also applies to any samples that are collected from a failure site.

4.6.3 Preliminary examination of failed part. At this stage possible causes of failure can be made purely from a visual examination, an understanding of the whole failure system, and an understanding of any background information. This might involve some non-destructive testing, but only if applicable and after the initial examination and discussions with people associated with the failure. Initially, a visual inspection will show failure features that cannot be observed in a macro or micro examination because a human eye has an extremely large depth of field and excellent colour perception. There can never be enough visual and nondestructive examination done in an investigation whether at the large systems stage or the macro stage and it is this information which is ideally suited for a computerised failure analysis expert system. Thus the expert system could provide the probable failure mechanism and indicate whether or not destructive tests should be undertaken. Destructive tests include mechanical testing and the cutting out of smaller samples for further detailed visual inspection. These destructive tests as well as being expensive, can destroy important clues as to the cause or causes of failure. Thus at this stage an investigator should be able to state "How" a failure occurred, i.e. fatigue, corrosion, before leading on to further investigations as to why the failure occurred.

4.6.4 Analysis and testing

After all the information has been gained from visual and other non-destructive methods, destructive tests, analysis, and examinations can be undertaken, with the understanding and coordination of all the parties involved. It is extremely important to get consent from all the parties involved before any cutting or damage is undertaken on the component for the provision of test samples. Careful records must be kept as to how, when and at what position samples were taken as this will help in the report and conclusion stages. The typical tests which could be undertaken are:

-Further visual and macro examinations as the component is cut open.

-Mechanical tests including, tensile, hardness, and fracture toughness testing.

-Fracture mechanics analysis including real and simulated service conditions.

-Metallographic analysis of sections.

-Chemical analysis including X-ray, infra-red, etc. to find composition of bulk, local, surface, corrosion products, deposits, or coatings.

4.6.5 Analysis of findings and conclusions

After the various results from the destructive tests and examinations have bee obtained, the formulation of conclusions, and writing of the report, which includes recommendations is the last step in the failure investigation. Including the results of the destructive tests in the expert system should produce a more accurate analysis of the failure situation. If the expert system is unable to analyse correctly the situation then the information gained from the investigation should be used to feed-back into the expert system to improve its future diagnostic ability.

4.7 Conclusion

The concept of failure depends on a person's perception. This perception of failure is affected by their educational background, the time and location of the failure, as well as the public and media understanding of failure. With the changing perceptions over time, acts of God and bad luck are being replaced by known failure mechanism and human error. It could be argued that human error has some part to play in all failures. The different and changing concepts of failure does not help in analysing the root causes of failure, which can be extensive. These causes of failure can be split into different failure modes and subdivided into failure mechanisms. However, knowing how a failure mechanism occurred, does not necessary mean knowing why that particular failure mechanism occurred and not another. This is extremely difficult and possibly beyond the capabilities of the present expert system, because to understand fully why a failure occurred, requires a holistic systems approach to failure investigations which is generally undertaken by an expert investigator. Although ideally, knowing the why of failure analysis is best, just knowing the how a failure occurred and its mechanism will aid an engineer, especially as each engineers' perception of failure is different. Capturing this knowledge from expert investigators is extremely difficult because although the experts might know what remedial actions to take for a given failure mode, knowing what steps lead to that conclusion is much more complex and is the thrust of the knowledge acquisition for this expert system development.

Chapter 5 Feasibility study for producing a failure analysis expert system

5.0 Introduction

Before embarking on research into expert systems related to failure analysis it is first necessary to establish if failure analysis can be addressed by expert systems. A feasibility study was thus carried out.

The feasibility study was loosely based on Waterman's (1986) and Turban (pp.542, 1990) designs, and is presented below. Turban comments on Waterman's design and gives his own interpretation of a feasibility study. His ideas were considered as a whole but Watermans proposed feasibility study was more closely followed.

The feasibility of an expert system to solve a problem will depend on the magnitude and complexity of the problem. According to Waterman (1986) a feasibility study should be composed of three parts:

1. "The Necessary requirements for expert system development"
2. "The Justification for expert system development"
3. "The Appropriateness of the expert system"

5.1 The necessary requirements for expert system development

(I) It is necessary that the task does not require common sense. When Waterman suggested that the task for the expert system to complete should not require common sense he meant that if it requires common sense then this will complicate the programming of the knowledge.

If the task can be broken down into a series of steps whose outcomes are governed by known rules and procedures, programming is easy via a rule based system, i.e. not common sense. Common sense programming requires a deeper understanding of the task and will require more complex forms of rules and procedures that are extremely difficult to program. Failure analysis cannot be completed by rules and procedures alone, though they are important. A failure analysis consultant uses a hybrid approach of both rules/procedures and common sense that has been built-up over his or her career (section 4). Thus, to program failure analysis knowledge requires a deep understanding of the interrelationship between cause and effect. However a trained engineer will also require some level of engineering common sense to understand the implications involved from any information given as a result of expert systems usage. This would suggest that a rule based expert system was not the most appropriate form of expert system for failure analysis. However a case based system might be more relevant as it mimics methodologies used by experts in failure analysis.

(ii) It is necessary that the task requires only cognitive, not physical, skills. Failure analysis might require some form of experimentation to evaluate data (facts) such as tensile strength or the exact material composition. These facts are **primary** facts in that they are based on first principles or known domains of knowledge, and thus could be held in either a database, or implied from other facts held in a database. These primary facts can be very difficult to evaluate, even through experiments, and thus rough estimates are taken. Secondary facts relate to the effect people have on a component or on processes that affect a component. These processes or influences are known as secondary mechanisms.
Though primary facts are considered important, true failure analysis is undertaken by an expert through a holistic systems approach using both primary and secondary facts. In the majority of cases the secondary mechanism, which is the contribution made by people to the risk of failure can be seen as the root cause of all failures. Trethewey and Roberge, (1994)

have further discussed this effects of people as the root cause of failures. In many failure investigations, physical experiments could be considered unnecessary for diagnosis. So, a systems approach to failure analysis used by an expert can be purely cognitive and based on known and implied facts from many domains. Thus, failure analysis is ideal for integration into an expert system.

(iii) It is necessary that the correct experts are selected. Information comes in two forms: Documented and Undocumented knowledge. Documented knowledge contributes a major part of the knowledge base in expert systems. Human experts possess knowledge that is more complex than documented knowledge. The human expert has experiences and engineering common sense, and through the correct formal reasoning, this knowledge can be formed into heuristic rules and standard case histories. These rules and cases, derived from the experts own undocumented knowledge, add to the quality and reasoning ability of the expert system, so selecting the right expert is important. Many organisations undertake extensive investigations into the correct choice of expert with the correct attributes.

Goyal et al. (1985) detailed the attributes of a good expert as follows:

a) The expert should be thoroughly familiar with the domain, including
-Task expertise built up over a long period of task performance.
-Knowledge of the organizations that will be developing and using the expert system.
-Knowledge of the user community.
-Knowledge of technical and technological alternatives.

b) The expert's knowledge and reputation must be such that if the expert system can capture some expert's expertise, the system's output will have credibility and authority.

c) The expert will commit a substantial amount of time to the development of the system, including temporary site relocation, if necessary.

e) The expert can communicate knowledge, judgment, and experience.

f) The expert should be cooperative, easy to work with, and eager to work on the project.

g) The expert should have an interest in computer systems, even if not a computer specialist.

h) The experts involved must agree on the knowledge and the approach to solve the problem.

i) The experts involved can articulate their methods of problem solving.

j) The task is not too difficult.

k) The task is well understood, and is defined clearly.

l) At least one genuine expert, who is willing to cooperate, exists.

The experts available for the development of this failure analysis expert system where:-

Dr Brian Mellor, Engineering Materials, Southampton University.

Dr Ken Tretheway, Engineering Materials, Southampton University.

Dr Alan Chambers, Engineering Materials, Southampton University.

Mr Robin Anstey, Metaltech Consultancy Services, Park Gate, Southampton.

Dr Roger Cook, Southern Materials Services, Broadstone, Dorset.

Dr Ken Reynolds, Technology Faculty, The Open University.

Mr Derek Bates, Materials Technology Limited, Lymington, Hampshire.

These people have many years of practical experience in conducting failure analysis on a wide range of components in various industrial sectors.

In addition expertise was available in the form of documented knowledge from published and unpublished work from the following organisations:-

1. Engineering Materials Consultancy Service, Southampton University.

2. American Society of Metals,
   Metals Handbook 8th ed. (1975)
   Metals Handbook 9th ed. (1986), Vol 11,
   ASM International, (1992) "Handbook of case histories in failure analysis"
   Volume 1 and Volume 2.
   Case Histories in Failure Analysis, 1979

3. British Engine Boiler & Electrical Insurance Co. Ltd, Technical reports.

To a lesser extent, information of a general nature relating to failure analysis was also available from the following literature. However, these sources were not extensively used.

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Other published works include (Dickson et al., 1992) (Van der Voort, 1975) (Bogaerts and Agema, 1992) (Collins, 1993) (Reynolds, 1991) (Ross, 1995) (Ryder, 1986) (Trethewey and Chamberlain 1988), (Naumann,1983), (Rollason, 1973)

Preliminary discussion with the above experts and perusal of the above documentation revealed that the failure analysis knowledge was very extensive.

However, both the knowledge of individual experts and documented information is highly unstructured. Knowledge must be structured for insertion into an expert system. Different expert systems methodologies require knowledge to be structured at different levels and it is the structuring of knowledge that is the complex task involved in developing an expert

system. Adopting a generic approach and reducing all complexities wherever possible to information which was well understood and ideally clearly defined, would make structuring the information easier. However, the field of failure analysis is similar to detective work where there are many theories of failures which are well understood, but the actual cause and effect relationship is poorly documented. There are many causes which have the same effect and there are causes which have many effects. This complicates the understanding of failure analysis. So a major task identified for this thesis was the structuring of this failure analysis knowledge. Failure and failure analysis has been initially defined in chapter 3. As the information available from both human experts and documented expertise is not specific to a particular industry, but it is rather generic, it was decided that the development of a generic failure analysis system was more appropriate given the expertise available. Also, it is unlikely that all this generic expertise will be known by all the experts, and thus the experts would benefit from a generic expert system. This was also agreed upon during informal conversation with the experts.

Additional requirements are as follows:

(viii) The task definition is fairly stable. There are no major new failure modes on the horizon, and the failure mechanisms to produce the different failure modes are generally well known. Thus, it is unlikely that there will be major new changes and the important aspects within the expert systems will be "cause-effect" relationships rather than the details of the different failure mechanisms. So failure analysis diagnosis is stable enough for an expert system. However, many new failure cases associated with known failure modes are investigated each day providing more information. The addition of this information into the expert system would aid analysis. This increase in knowledge can be used to the expert system's advantage especially when case based reasoning is the technique employed in the expert system, i.e. the cases can be used to update the expert system.

(ix) Conventional (algorithmic) computer solution techniques are not satisfactory. This is a very important consideration, because if a conventional (algorithmic) computer program will successfully analyse failures, why go to the expense and trouble of producing a complex expert system for a simple algorithmic domain problem? Failure analysis is a heuristic process, involving a holistic approach to general rules of thumb, procedures and facts. Thus, a pure algorithmic process (numerical manipulation) although easier to implement, could not deal with the information used in failure analysis and thus is unsuitable for failure analysis.

(x) Incorrect or non-optimal results can be tolerated. The expert system can be developed to assist and complement an expert rather than to replace the expert. The expert system can be designed to work by fuzzy matching between the actual entered information and the stored failure case histories. Also, when a case is matched with a diagnostic situation, it can then be

up to the expert to select or reject a failure mechanism from a selection of cases given by the expert system. Thus, incorrect or non-optimal information can be tolerated firstly due to fuzzy matching and secondly due to the expert's selection. Designing in the ability to deal with incorrect or non-optimal information, means that the expert system can be used as both a design tool and a diagnostic tool. A design tool means that a component design with its associated materials, environment, and loadings can be analysed by the expert system for its propensity for failure.

(xi) The domain must be well bounded and narrow. The domain of failure analysis is wide. It covers many material compositions, many physical effects (magnetic, electric, radiation, temperature, etc.), many mechanical effects (stress, shear, impact, expansion) and combinations of these. In addition there are many different generic components with different failure modes. A detail description of the nature and complexity of failure analysis can be found in the previous chapter (chapter 3). Therefore, in the first instance, it was decided that the expert system would concentrate on a narrow band of materials and components in its prototype system. This could then be widened to incorporate more knowledge in the full system.

(xii) The vocabulary has no more than a couple of hundred concepts. The vocabulary has many terms and these terms can sometimes be confusing in their exact meaning and reference. For example, cracked, fractured, ruptured and broken, all describe a failure but have a different precise meaning. Therefore, a part of the project was to develop a thesaurus of common associated failure terms, and examine different methods with which to deal with the complex semantics involved in failure analysis (Chapter 11).

(xiii) The availability of data and test cases. The data for the system have been taken from real cases and from books and articles. The case histories are from actual failure analysis investigation undertaken by The Engineering Materials Consultancy Service at Southampton University. This majority of information has accumulated since 1981. Acquisition of this key knowledge resource is seen as central to the success of this and any future expert system.

5.1.1 Copyright Laws involved in knowledge acquisition. In taking any information from any source such as a book, an article in a journal, or even electronic media, the user of that information has to be careful not to break the copyright laws. This greatly affects the development of any information system especially electronic books (multimedia system) and knowledge based systems. To overcome the problem of copyright laws, (Millard, 1996) information has to be original. This means that photographs, and drawings cannot be copied directly, but drawings can be redrawn, just as photographs can be retaken. Text cannot be copied but it can have its meaning transferred. This involves rewriting a piece of text in a

revised summary way and to include references to the originator. If it is critical to have the information in its original form, whether a drawing, photograph or a piece of text, then a copyright agreement must be sought from the copyright holders, who could be the original publisher, the author, or a studio (photographs or music for multimedia). This is a difficult and time-consuming process, especially for electronic media documents which generally require many sources of information. In the present case information for the failure analysis expert system could be based around real cases investigated by the Southampton University Engineering Materials Consultancy Service. The consultancy service holds the copyright on all it reports. Therefore, photographs and other information can be copied directly.

The expert system itself under present laws is copyright protected. Under the British Governments "Copyright Rights in Databases Regulations 1997" (CRDR) a compilation of information, will gain copyright protection provided that it is original in the sense that it is not exactly copied form an existing work. Thus, even though a compilation's contents are entirely commonplace, if the compilation required much "sweat-of-the -brow" type labour then it is copyright protected (Angle & Quinn, 1998). However, this style of copyright protection does not extend to computer generated databases because under section 9(3) of the Copyright, Designs and Patents Act 1988 (CDPA) it states that a person who undertakes the arrangement necessary for the creation of a computer-generated work is taken to be its author. Thus a table of calculated fatigue life prediction produced from a computer program, do not have copyright protection but the program itself holds copyright protection for the author of the program. Thus a compilation of information (database, expert system, knowledge based system) will not qualify for copyright protection unless it attains a particular standard of originality, namely, that it is, by reason of the selection or arrangement of its content, its author's "own intellectual creation" (CRDR section 3(a)(1))(Angel et al, 1998).

As adapted from Angel et al (1998) there are three people (or organisations) who could be considered to be taken as the author of this expert system. They are:

(I) the person who enters the expert system knowledge, i.e. Jasper Graham-Jones;

(ii) the person (organisation) who paid for the expert system, arranged for its set up and for the data to be input, i.e. Southampton University;

(iii) the author of the software used to create the expert system, i.e. CBR Express Inc and others.

The main author with the most rights is seen as the person who enters the information. However, if the copyright was infringed then all author could sue for redress. Thus the expert system's copyrights are heavily protected.

There are a few exceptions to infringement.

(a) Research and private study as long as this was for non-commercial purposes. Although, the regulations are somewhat vague as to what extent this covers, i.e. when does it become commercial.

(b) Being a lawful user, i.e. a person would not infringe if he is doing something which is necessary for his right to use the database. Thus is the user is allowed to copy the database in order to fix a bug which prevents him form his lawful access of the data, but he is not allowed to copy the data in order to discover the structure for the purpose of creating a rival product.

Thus the expert system could be examined and developed by other undergraduate or post-graduate students for research and private study, but such a student could not examine the expert system's structure or contents to produce a rival product.

5.1.2 Security of confidential knowledge (Coleman, 1996).

As stated above, some information could be taken from real failure analysis cases from the Southampton University Engineering Materials Consultancy Service. These case histories originate from studies undertaken on behalf of companies and other organisations, and this information is both confidential between the consultancy service and the company/organisation and copyright protected. Therefore, not infringing this confidentially is important especially as the consultancy service could be legally liable. Thus, information held within the expert system will not include any references to the company. This includes brand names, part numbers, logos, in either the visual (photographs, graphical, drawings) sense or written (text) sense. Generic names will however be used.

5.2 The justification for expert system development.

Waterman (1986) listed the following, of which one must be present, to justify the development of an expert system.

(i) The solution to the problem has a high payoff (i.e. Economic feasibility). The cost of developing the expert system has presently been met by the Engineering Materials Consultancy Service, the Department of Engineering Materials and the University of Southampton. The exact cost is not known yet. Another area that is not clear is the cost of maintenance, which can sometimes be higher than the development costs. As these figures are not available, it is too early to predict any anticipated payback. However it is well known that the development of an expert system is a very expensive process,

The aim of this research is to develop an expert system to assist in failure analysis. This, by itself, will tend to speed up failure analysis and so reduce its cost and hence the actual development costs could be recouped. However if the failure analysis system is so developed that it can be also used to predict and so prevent failures, the economic returns will be much

greater. For example, as quoted in Trethewey, K.R. and J. Chamberlain, (1988) "a 1971 British government study of the cost of corrosion concluded that the total cost to the national economy was £1365 million (1971 prices) and about 3.5 per cent of the gross national product. Of this, about one-quarter could be saved by better and wider use of well established corrosion protection techniques. (Hoar, 1971)". This did not include the agricultural industry which was studied by the University of Manchester Institute of Science and Technology in 1981. They reported that corrosion was costing the agricultural industry £600 million per year of which 50% could be saved by existing corrosion control technology. (Editorial 1982) (Trethewey and Chamberlain, pp.1 to 15, 1990).

Thus when considering that the expert system could reduce the propensity for failure and the actual cost of failure, the development costs are very minimal compared to anticipated savings even from one major failure of which examples are given above. If only a small portion of these costs could be saved then a high payoff would be achieved.

(ii) The expert system can preserve scarce human expertise so it will not be lost. As previously stated, the expert system can store the knowledge of different failure cases held in the Engineering Materials Consultancy Service archive files. Although these files will never be lost, the access to these files and thus the knowledge they hold is difficult. In addition the undocumented background information to these files would be lost when the consultancy's members retire or move to different appointments. Thus, the expert system will preserve the consultants' undocumented knowledge and make the files more accessible. Additionally, if for some reason, the files are destroyed, either accidentally (fire, flood, etc.) or on purpose (lack of storage space), this information will still be held within the expert system. It must be noted, that the inclusion of all the cases within the expert system would be a considerable task and some cases may not be appropriate for failure analysis investigations. Thus, only cases that had a clear conclusion and were actual component failure investigations will be included.

(iii) The expertise is required in many locations. Failure analysis information could be required in many locations. This could be either at the scene of an investigation in which a portable computer could be used or within a design studio via a wide area network (i.e. the Internet). These multiple locations would aid the engineer by providing information where it is required which could reduce the time to diagnose the reason for failure and suggest remedial measures. Such remedial measures could be implemented on location and the result could be analysed, thus saving trips back and forth between the failure location and the laboratory. There is no need at present for information to be at multiple locations. However, if this facility was provided, it then could be used on-site during initial failure investigations to ensure that all appropriate information was collected.

(iv) The expertise is required in hostile or hazardous environments. It is very unlikely that any person would wish to undertake failure analysis in a hostile or hazardous environment. However there are situations in which the environment is either dusty or moist. In these situations, specially protected computers are available, on which the expert system could be loaded. Nevertheless, it is very unwise to think that this or any expert system is a "quick-fix". Failure analysis requires a detailed analysis of the whole failure situation.

Other factors to be considered to justify the expert system are as follows:

(v) The expertise the expert system provides improved performance and/or quality. The failure analysis expert system proposed will draw the experts' attention to different factors associated with different failure mechanism and will support the experts' own knowledge. Thus the expert will be reminded of different possibilities and therefore the expert system will provide an improved performance and quality to the experts' decisions.

(vi) The expert system can be used for training. Ideally when a user is using the expert system, they are actually training themselves to give more consistent answers to any failure analysis problems. So a good expert system would make training in failure analysis an integral part of the systems. Some expert systems just give an answer. As failure analysis knowledge for diagnosis is complex, one ideal answer is not possible. There is a saying "That given one failure situation, two failure analysis consultant could find three very valid answer to the problem". Thus, the expert system could provide the user with several possible solutions. The user then looks through the stored information on the different failure modes before making a decision. In this way the user learns about how the different failure mechanisms are associated with different components, materials, and other factors.
Failure analysis is taught in Engineering courses at universities normally by examining a collection of failed components. An expert system in this area would contain more data than normally provided to students and if structured to be used in an interactive manner, it would be useful as a teaching aid. Thus the expert system could be used as an interactive computer based learning application for students and young engineers.

(vii) The expert system's solution can be derived faster than a human can provide. If more information is provided to the expert than would personally be known, then this should lead to a faster decision.

(viii) The expert system is more consistent and/or accurate than a human. The expert system is not more consistent or accurate than a human as it requires a human with whom to communicate. However through using the expert system, the decision that the human user derives should be of a higher consistency and accuracy than if the decisions were arrived at by humans alone, due to the greater amount of information being readily available.

5.3 Conclusion to Feasibility Study

In considering whether it was feasible and appropriate to develop an expert system suggestions by Waterman were followed. He suggests that the nature, scope of the problem and the complexity of the task be considered when deciding if developing an expert system is appropriate. He also suggested that the problem should have a symbolic structure and heuristics should be available for its solution. In addition it is desirable that the task be decomposable for development and should be of a manageable size; with a practical value that is neither too easy nor too difficult for a human expert.

Thus in conclusion to Waterman's suggestions, although failure analysis is a complex task with little easily available structured information, it is feasible to develop an expert system to conduct failure analysis as long as the following points are borne in mind:

1. The knowledge required for failure analysis investigations is extremely varied and complex. This knowledge is unstructured and cannot be wholly captured in rules and procedures. A case based reasoning expert system would be able to capture this unstructured knowledge in the form of cases far easier than a rule based system.

2. The capturing of knowledge in the form of cases is ideal, because this will preserve the knowledge held by experts, consultancies and other organisations who undertake failure investigations as they report their investigations as actual cases.

3. The expert system should give suggestions rather than single answers. This would also indicate the development of a case based reasoning expert system rather than a rule based system.

4. The expert system should be able to analyse, predict and prevent future failures from incorrect and non-optimal information. This would indicate that the use of fuzzy matching logic is required

5. If the expert system on failure analysis is to be used as a teaching aid an appropriate structure should be used from the start. This structure should be easy to use and contain clear explanations and images which are ideal for didactic purposes.

6. A better understanding of the interrelationships between the different factors associated with component failure and the propensity for failure is required. This involves understanding how experts organize failure analysis knowledge and how component failure analysis investigations are actually undertaken. An understanding

of how this information can be organised and structured into an expert system is required.

Chapter 6 Hardware and software selection for an expert system

6.0 Introduction

The complex process involved in selecting hardware and software is based on a match between the knowledge to be represented, and the built-in features of the software tools and associated hardware. From the author's experience the selection of software and hardware, initially is based around what the programmer and potential users either owns or has a high degree of familiarity with.

6.1 Hardware selection

In the past, computer systems were based around mainframe computers (IBM, ICL, Digital, Hewlett Packard, etc.). This made the hardware/software selection process more complex, because computers from different manufacturers required different software packages. In the mid-1990's the majority of developments in expert systems and other software systems are based around small high performance personal computers that are either stand-along or networked to other computers (local and wide area networks). Presently there are three main hardware platforms, IBM compatibles, Apple Compatibles and Unix based computers.

The hardware selection was primarily based on two major criteria:

(1) Which hardware platform had the greatest user base, now and is this predicted to continue to be the case in the future?

(2) Which hardware platform is used and or preferred by the experts and other users?

The three main hardware platforms are analysed against several important selection criteria and compared to the ideal scenario below:

Selection criteria	IBM Compatible	Apple Compatible	Unix Based	Ideal Scenario
User base	Very High	Low	Low	Very High
Software availability	Very High	Average	Low	Very High
Speed	Average	Average	Very High	Very High
Hardware maintenance	Complex	Very Easy	Complex	Very Easy
Cost	Cheap	Above average	Expensive	Cheap

Apple compatibles and Unix based computers are thus not suitable due to the low user base, initial high equipment cost and low software availability.

Currently (1997) IBM compatible computers capable of running Microsoft Windows 3.1 are the systems with the biggest user base, i.e. the most intensively used and popular platform. This has been due to low equipment costs and high software availability. This has resulted in a large marketplace which has led to further development and growth for this type of compatible hardware and its associated software. This is ideal for an expert system which wishes to have many users on standard computer hardware platforms. Although Windows 95 and Windows 98 are the most recent additions to Microsoft's product range, many computer are still unable to run this software operating system. However it is very likely that most users will convert to higher versions of the Microsoft Windows operating system. This will not cause any major problems because programs designed for Microsoft's Windows 3.1, are able to run on higher systems, such as Windows 95, Windows 98 and Windows NT. However after these system there is no guarantee of the platform type, but through the uses of emulators, as presently used in Windows for Dos, Unix, and ZX Spectrums, it is envisaged that future systems will be able to run older systems.

Discussions with different failure analysis experts (section 5.1 part 3) confirmed that they were using IBM compatible personal computers. Thus the choice of IBM compatible personal computers satisfied both major selection criteria and hence an IBM compatible computer capable of running Windows 3.1 was chosen as the minimum requirement. The initial technical requirements, therefore, meant that a 386 processor with four megabytes (4Mb) of random access memory (RAM) and a Video graphical adapter (VGA), card with 512kB of graphical memory was the minimum requirement. The minimum would only just run the system; A preferred system would be based on a 486 processor, with at least 4Mb of RAM and a 1Mb graphics card and a super video graphical adapter (SVGA) graphical display. However the systems described above have been superseded by more powerful computer systems such as the Pentium II processors and others, to the point where users can only buy 486 processor based computers in the second hand market. Thus virtually all IBM comatible machines could run the software.

6.2 The software selection criteria

There are many software methods in use to develop expert systems, such as programming languages (Prolog, Visual C and C++, Visual Basic, Lisp, etc.); Rule-based expert system shells (Crystal); and Case-based reasoning tools (CBR Express). Each has advantages and disadvantages as shown later in section 6.4. The choice is very important in the development of an effective expert system. The majority of expert system developments use expert systems shells, as detailed in section 3.

There are many different Expert System Shells and programming languages on the market today. They range in price and capability, and more importantly they range in usability in that some systems are very much harder to program then others. In general the harder the system is to program then the more capabilities the system has, but it takes a longer time to program and do we require all the capabilities that the system has to offer? All expert systems have the same structure. This is a user interface, for the acquisition and representation of knowledge, a knowledge base, an inference engine and a blackboard, as detailed in Figure 2.2 and section 2.1. The difference between expert systems and expert system shells is that in a shell all the components of an expert system are there but there is no structured knowledge in the knowledge base. Additionally the quality of the user interface will generally be less in a shell than in a full system. In contrast when programming languages are used, rather than an expert system shell, several disadvantages and advantages may be expected. Generally computer programming languages are considered difficult to program. When using a computer programming language, all internal structures associated with expert systems have to be designed, developed, and built. This is a very labour intensive and complex procedure. It could be argued that the inherent flexibility in developing an expert system in this way is advantageous. However, there may be enough features already included with in a commercial expert system shell.

Goyal et al (1985) developed and summarised a number of issues in the evaluation of software for selection. Thus the following criteria were taken into consideration when selecting the software for the expert system:-

Can the tool be easily obtained and installed? This includes cost factors, legal arrangements, and compatibility with existing software and hardware. Goyal et al (1985)

Cost; The initial cost of the system is just one part and this can be a very small part overall. Other costs must be considered, such as the runtime licence, site licence. The run time licence cost is the cost of the copyright agreement to allow use of a copy on a machine. The first runtime licence is included in the initial cost of the system but if there is a number of computers in an office or class room then each computer will require its own runtime licence. A site licence is similar to a runtime licence but it covers the complete site of a company or college. Judgements have to be made on how many machines are going to be used that require the software installed on them and occasionally judgements to do with what level of interaction will be allowed. The level of interaction relates to the amount of modification that a user can make to the system. For example, if you develop an expert system and then want to sell or give the expert system to another person, then another runtime licence has to be purchased. What is purchased could be a complete development system including your expert system program or it could be your expert system program with the development system

locked up in the background. A locked-up development system will mean the end user cannot make his own expert system by deleting your expert system. This is fair to the original shell developer, but the major draw back can be that the end-user's ability to change or redesign your expert system to their particular requirement is limited. In most commercial systems this does not matter as much as it does in the research world. Another major costing to be taken in to consideration is maintenance. This can be higher than all the other costs combined. The maintenance costs include; the annual developments and runtime support from the software vendor, internal software and hardware user support, training, future hardware and software systems upgrading such as additional interface drivers for printing, and linking to other software. The maintenance cost is especially high in complex computer systems.

Compatibility; i.e. is the program compatible with other programs on your computer. In the past this has been greatly ignored, although today this is changing with the introduction of the Windows systems from Microsoft, Apple, and Unix. There still can be many problems in connecting a particular type of multimedia application, database, expert system shell or programming language together to form a fully integrated expert system. This can be partly solved by the purchase of extra drivers or converters from the different companies involved. However this can be a considerable problem, especially if different users use different platforms (Dos, Windows 3.*, Windows 95, Apple, Unix, etc) and use different versions of the same software. Thus a multitude of software drivers (printer, graphics, etc) have to be considered. For these reasons it is important in the majority of cases to use the most common standard presently available and then make it compatible with as many other standards as possible.

The stability of the company, i.e. will the company still be trading in ten-fifteen years time with all the product support available. This relates back to the compatibility issue, because an unstable company is unlikely to support fully your software choice and it is unlikely that the software would be fully developed to be compatible with other systems.

Performance, How does performance relate to cost, for a given quality of graphics, processing speed, and are there any extra tools included? What is the stability of the system? , i.e. will it crash when undertaking a complex set of calculations? Does the speed match what is required by the problem?
Can the tool handle the expected form of application data, i.e. continuous, error-filled, inconsistent, uncertain, time-varying, etc? (Goyal et al. (1985))

Number of Users, How many people use the software today and what do they think of it. How user friendly is it? Has the tool been successfully used in a variety of application domains? Is there a delivery (consultation) vehicle available? Are many copies of the

application required either for development or for the distribution of your developed expert system?

The inference technique -Does the performance of the inference technique (searching technique) provided match the problem searching technique. If this is so then the program is more likely to be successful;
What kind of knowledge representation schemes does the tool provide? rules? networks? frames? objects? cases? backward chaining? forwards chaining? . Do these match the intended application? (Goyal et al. (1985))

Ease of Programming; Possibly the most important factor in deciding which expert system or programming language to buy will relate to how easy it is to program. Frequently the programmer (Failure analysis expert) may know a lot about his subject which he wants to incorporate into an expert system (domain knowledge, failure analysis) but very little computer programming knowledge. For a computer programmer, this problem is very much reversed. It would take far too long to teach one the other's domain knowledge. So it is better to purchase a system that is programmable by the domain expert. This means simple-to-use natural language interaction in the development of the system. This can in many cases rule out complex programming languages such as Lisp, C and C++, Prolog, etc. which can be used to make expert systems.

Other issues to be considered in programming are as follows,

-How difficult will it be to expand, modify, or add a front or back end tool. Is the source code supplied or is it an extra cost if it is available at all? (Goyal et al. (1985))

-Is it simple to incorporate programming language functions to compensate for necessary features that are not built-in? (Goyal et al. (1985))

-How well is the tool supported? (Goyal et al. (1985)). Is there after sale-help and does this cost any extra? Is the documentation with the tool of a high standard and does the supplier have a system of upgrading the software and documentation? Will this policy dealing with later upgrade of the tool be backward-compatible? .

Upgrading issues in software selection

An important aspect in computer applications, especially expert systems and knowledge based systems, is that the application should be easy to use and upgrade. This is a major design consideration in the structure and knowledge representation within the expert system and the choice of the expert system shell. This is especially so when one considers the considerable task of knowledge acquisition which is involved in the collection and storage of many failure cases. Therefore in the design of the expert systems structure, an important part of the up-gradability of the expert system is to allow the knowledge to be transferable to other more advance expert system shells, when these become available. This can be achieved by the knowledge being stored as cases that are accessible as DOS text files. DOS text file can be easily acquired by, and transferred to, other systems. However this might not be the most successful method, especially in complex object oriented programs where the associated links might be lost. Thus other methods and standards have to be examined which are compatible with possible upgrades.

Universal design to aid access for people with differing abilities

It cannot be assumed that every possible user of a failure analysis expert system has the same physical, mental and cognitive abilities. Millions of people in the world could benefit from access to computer information systems, such as expert systems. Thus a universal design related to software and hardware would benefit all users, both with or without disabilities. In many cases, people may experience difficulty in using software purely as a result of the environment or unusual circumstances. For example the following engineers may benefit for a universally accepted designed software:-

(I) Engineers and students totally new to the expert system.

(ii) Engineers in industrial settings, i.e. noisy and poor lighting conditions.

(iii) Users who have visual, cognitive, language, auditory and physical disabilities problems.

(iv) Users who have a congenital condition or are aging.

(v) Almost anyone especially if they are tired or ill.

In 1994 it was estimated that in America there was over 40 million people with some form of disability. (Vanderheiden,1994) Therefore in order to design an expert system for the maximum diversity of users, it is important to examine the choice in development software, and the final application produced, together with the associated hardware. Therefore in the development of the expert system for failure analysis the following factors were taken into consideration when choosing the expert system development tool and in the design of the expert system's environment.

(I) To design the expert system for the greatest number of users without the need for special adaptive software or hardware.

(ii) To design the expert system so that it will work with the special access features built into the operating system and to be compatible, or not conflict with, any third party access features, software, or devices for those who cannot access the software directly. For example it was decided that the use of sound had to be an all or nothing scenario, because visually or cognitively impaired users would either use third party speech recognition software or have to use the built in system. Trying to use both can cause problems in compatibility and conflicts with the software and operating system.

(iii) To make sure that documentation, training and support systems are accessible. Although this is outside the particular research scope of this thesis, it is still something to consider for future developments.

A more detailed analysis of the problems involved and solutions to the design of the expert system for greater accessibility that have been considered are detailed in Appendix 4.

6.3 Software Selection Conclusions

Table 6.2 presents the results of analysing various software options against the software selection criteria which was discussed in section 6.2.

Selection Criteria	Programming Languages Visual Basic, C++, Access, Excel	Tool Book	HTML Web based	Crystal Rule-based reasoning (DOS based)	CBR Express Case based reasoning	Ideal Scenario
Software Costs Maintenance Costs Run-time Licence	Low High Low	High Average Low	Low Low None	High Average Average	Very High Low High	Very Low Very Low Very Low
Compatibility	High	High	Very High	Low	Average	Very High
Company Stability	High	High	Not applicable	Unknown	Average	Very High
Performance	Average	Low	Very Low	High	Very High	Very High
Number of Users	High	Average	Very High	Low	Very Low	Very High
Inference Technique Match	Very Low	Very Low	Very Low	High	Very High	Very High
Ease of Programming	Very Low	Average	Average	High	Very High	Very High

Selection Criteria	Programming Languages Visual Basic, C++, Access, Excel	Tool Book	HTML Web based	Crystal Rule-based reasoning (DOS based)	CBR Express Case based reasoning	Ideal Scenario
Ease of Upgrading	Very Low	High	Very High	Low	Very High	Very High
Accessible for different users	Low to High	High	High	Low	High	Very High

Table 6.2

The most important selection criteria are ranked as follows, the inference technique match, the ease of programming, performance, the ease of upgrading and cost, where inferencing technique was the most important. Thus the ideal software package would cost nothing and would perform the same inference task of a consultant at great speed, yet, still be extremely easy to upgrade and program. Hence Table 6.2 suggests that the use of a ready made expert system shell (knowledge representation environment) would be the best approach in programming the failure analysis diagnostic expert system. Although an expert system shell would not ideally be suited for our particular application, it was felt that actually writing the computing components normally required for an expert system (chapter 2) would be like trying to re-invent the wheel. In addition, the author's experience is in the acquisitioning, structuring and representation of the failure analysis knowledge which has to be captured within the expert system. The main thrust of the research is the knowledge engineering of failure analysis information and not the development of an expert systems shell. Thus, instead of using Visual C++ or Visual Basic, a commercial application shell was considered as it was thought it would be difficult and unproductive to improve on existing commercial shells. Many rule based expert systems shells were examined (Crystal, Clips, Knowledge tree), but it was felt that a Windows Case Based Reasoning approach was best suited to our proposed diagnostic application. The advantages that a case based reasoning gave over other rule based reasoning systems are detailed in section 2.4.

In conclusion, the failure analysis expert system was developed using a Windows case-based reasoning package (CBR EXPRESS from Inference Europe Ltd.) using CasePoint as a run-time application and a graphical user interface development package (ToolBook from Asymetrix Corporation). It is also possible to make links to either Hyper text Markup Language (HTML) for world wide interface or Microsoft Visual Basic for the analytical calculations. In the authors' opinion, the case based reasoning package selected, although not ideal in that it is expensive, appears well suited, especially in term of performance and ease of programming, for the design and development of diagnostic expert systems, especially in the area of failure analysis, (Graham-Jones et al., 1994) (Thomas and Graham-Jones, et al., 1994).

6. 4 Details of CBR Express

CBR EXPRESS is an application of ART-IM, the Automated Reasoning Tool for Information Management from Inference Corporation, which is used to develop case-based expert systems or policy-management programs. ART-IM is an artificial intelligence programming language and environment supporting the integrated use of case-base reasoning, forward-chaining rules, schemes (frames), object-oriented programming (messages and methods), database access utilities, and interface support, for PC's, mainframes, and many models of workstations. (CBR Express reference manual, 1993). Although the case-based reasoning application developed could use CBR Express as a run-time application it was felt that with the recent development of a purpose built run-time application for CBR Express called CasePoint would be used.

There are several advantages of using CasePoint rather than CBR-Express as a run-time application. These are:-

CasePoint has Rule Support, allowing users to create rules to answer automatically questions from either description terms or answers to prior questions. The use of rules is detailed in chapter 8.

CasePoint supports Maximal Discrimination Question Ordering, or Strata Ordering, which orders questions more intelligently than the standard question ordering algorithm. This means that the first top five matching cases rather than only the top matching case are considered by the expert system when assessing which questions should be asked.

CasePoint supports case bases or ToolBook files held on read-only paths such as CD-ROMs and networks.

More information can be provided about the case base. These functions allow a cooperating application to retrieve information about actions and questions for a given case. This improves the user's understanding of how the expert system came to a conclusion.

CasePoint supports Internationalization (European) character set.

6.5 Details of TOOLBOOK

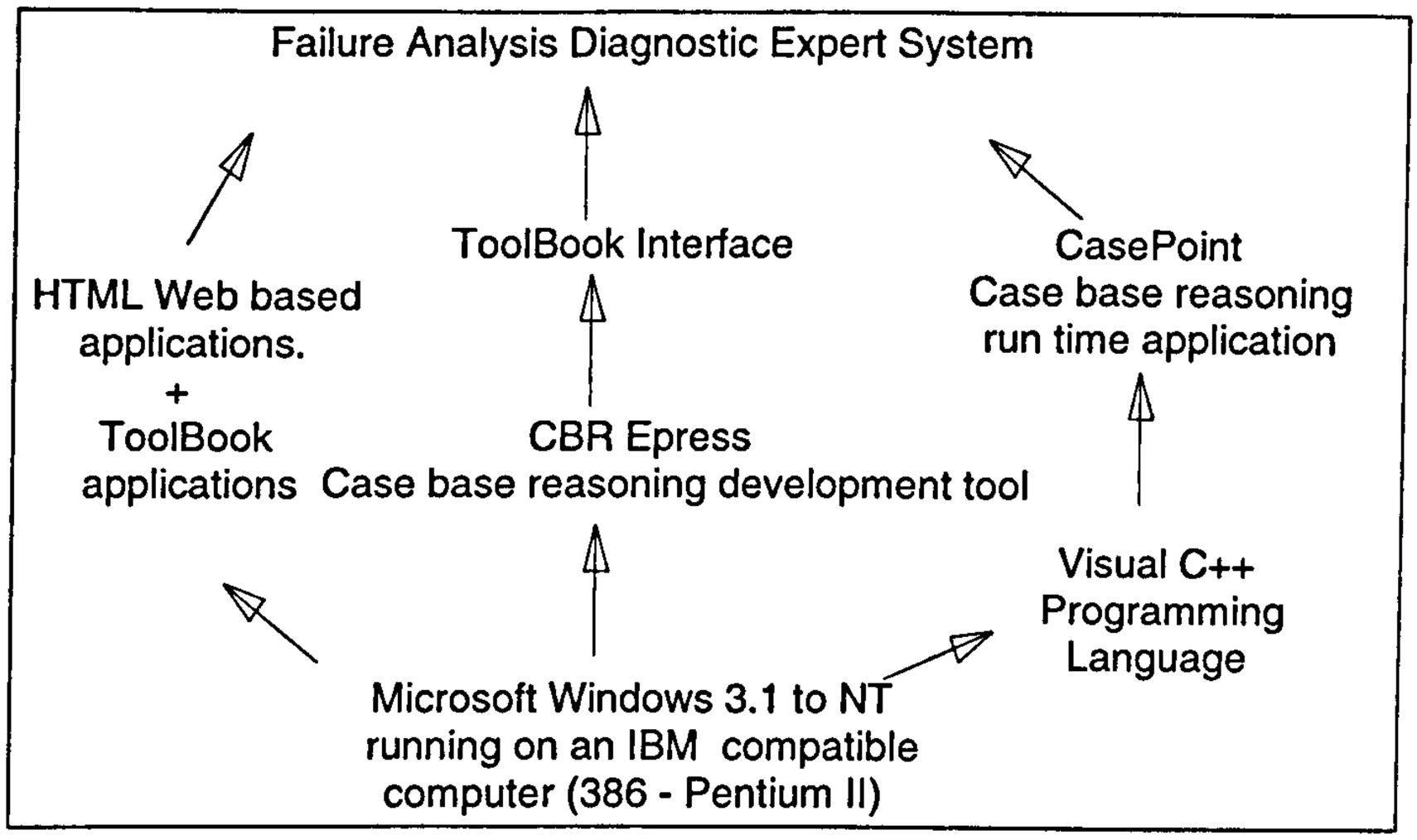


Figure 6.1 Computer software hierarchy adopted.

ToolBook is an application development system for Microsoft windows environment. Typical applications include reference systems, data base front ends, content and educational applications, kiosk information systems. A ToolBook file (*.tbk) can be made up of many other ToolBook files. A book is also a metaphor for the components in a ToolBook file. These typically include, graphic objects, Text fields Viewers (Windows), pages, buttons, and backgrounds. An application can be built by creating pages, placing objects on the page and then writing scripts in ToolBook's Open script language so that objects perform the required actions.

The original graphical user interface (GUI) for CBR Express is written using TOOLBOOK from Asymetrix Corporation. Different versions of CBR Express required different versions of ToolBook. These were CBR Express version 1.3 required ToolBook version 1.54, whereas the newer versions required versions 2 and 3 respectively. ToolBook is unable to alter the graphical interface of CasePoint as this is developed in Visual C++ version 1.54. The TOOLBOOK interface contains scripts (programming codes) that link to ART-IM to ensure that knowledge acquisition and representation of the different case-bases is simple to execute. The original TOOLBOOK GUI can be extensively modified, to include functions more relevant to failure analysis. However, the main uses has been in the development of multimedia applications on different aspects of failure analysis These might include applications detailing different failure modes (chapter 12).

In conclusion Figure 6.1 shows the computer software hierarchy adopted based on the international Microsoft windows operating system.

Chapter 7 General approach to using the failure analysis expert system

7.0 Introduction

The expert system work on two levels,

1. Before failure to improve the reliability of the component
2. After the component has failed

The main difference is that questions about the fracture surfaces are not relevant before failure has taken place. By a suitable choice of questions this makes little difference in most situations, but obviously information on the fracture surfaces does provide a very valuable input if failure has occurred. Thus questions that ask about the fracture surface, extent of surface damage, the time of failure and other can be left unanswered. However questions in general have been kept as broad and generic as possible so that if analysis is undertaken before failure it will not greatly matter. This is further detailed in section 9 on the analysis of the questions.

The procedure in using the expert system for failure diagnosis is outlined and then further detailed below:-

1. Examine the component either for failure or reliability investigations. From this a description can be entered into the expert system.

2. Answer some questions.

3. The expert system suggests appropriate failure cases related to the information entered associated with the description of the situation of the component. The appropriate failure case is the failure case with the highest matching score tothat of the situation described. Details on these cases are selected by using the browser facility.

4. Browse the appropriate actions related to the cases with the highest matching score as above.

5. If there are no matching cases, save the information entered for either development into additional cases or fine tuning of the whole expert system by an expert in failure analysis.

7.1 Enter the description. The first step is to enter a natural language description of the component, whether it has failed or not, giving materials, environmental and loading details. This information has to be gathered from the component either via a failure investigation or through a process of design and value analysis. The methodology involved in failure investigation has been covered in chapter 4. The failure analysis expert system would

normally be used during the initial stages of an investigation, so that the consultant could get an approximate idea as to the range of possible failure mechanisms and their remedial actions.

The expert system shell used, CBR Express runs an initial search on this description, looking for cases whose descriptions are similar to it. If, however, the user is unable to provide a natural language description of the component, the question answering stage of the expert system can be entered immediately by imputing "help" or any two letters which do not make a word excluded from the search. A list of excluded words is given in section 11.2.

If a description of the problem is entered, the description is obviously very important. The object is to write a sentence or short paragraph that describes the symptoms of the problem, or the characteristics of the product, as the operator is likely to phrase them. For instance, here are two examples:

"The steel surface always comes out rough in seawater."
"The shaft went through reverse bending before it failed."

These are considered as average descriptions. Better descriptions are those which include more keywords that can fire rule. For example:- "A brass nut has failed in seawater". This description picks up on the keywords, Brass, nut, failed, seawater, and answer questions on the material, the component group, and its environment. A bad description would mean many words which cannot be visualized, such as "filler" words, and very few key words were included. Keywords are words which fire rules and these are detailed in chapter 11. However, bad descriptions are not really a problem because the expert system simply ignores most of the general "filler" words used in descriptions, such as most articles, prepositions, synonyms and verbs (the *ignored words).* These ignored words are listed in section 11.2. The software also strips off most punctuation and suffixes, reducing the amount of data to process during the search. From the two descriptions written above. The expert system concentrates on the parts with the greatest meaning, i.e. the keywords and nouns which form the backbone of the sentence and so extracts the sense.

" steel surface rough seawater "
" shaft reverse bending failed"

Making the description complete, accurate, and precise is very important. It should contain all of the pertinent information about the failure problem. This greatly aids initial searches, especially if keywords are activated, which answer questions via the built in rule base (see chapter 11). There are various ways the user might express the description. For instance, the

failure case title "Fatigue failure due to sharply-edged formation" has the following description:

> "Fatigue failure due to sharply-edged formation (corner, notch, small fillet radius, crevice, holes, craters) due to high hardness of surface and high stress cycles, surface and sub-surface defects with small radii, lead to stress concentrations and high Kt, Kf values leading to cracks"

The matching algorithms will score the user's search description based on how much of the search description is contained within the case descriptions. For instance, if the case description was exactly the same, word for word, then the search description shown above will provide a perfect match. If the user enters an extremely long search description and all the text of the search description appears within the case description, it will also be concluded that the two descriptions are similar. However an exact match is highly unlikely, what is more likely is that a search description will be similar to several cases because the additional words would match with other failure cases. These cases are given a similarity score, up to a set maximum. The maximum similarity score is set within the option's menu under preferences, and this can be within the range of 0 percent to 100 percent. However, within this expert system the maximum score is presently set at 30 percent. So when the case description is entered as a search description for the failure case, i.e. an exect word match, such as "Fatigue failure due to sharply-edged formation" then the expert system returns the maximum match against this case giving the maximium set score of 30. However if this is tried the returned matching gives 34 because the word "fatigue" has been picked out and used to answer a question "Does the surface look like a fatigue failure". The cases returned will depend on the individual case descriptions, the associated rules and questions, and the weightings given to these descriptions, rules and questions compared to others in the expert system. As the expert system is under continious improvement, by the addition of cases, rules, and question, and the adjustment of weighting, the matching scores gain presently cannot be garrentted for the future. If in the above example, more cases related to fatigue were entered into the expert system then the relative weightings of these fatigue related cases would be higher than the other non-fatigue cases. Hence the similarity matching score cannot be given as a fix number, because even a very small change in the expert system will affect the score. Thus for the description "Fatigue failure due to sharply-edged formation" the expert system presently also returns a similarity matching score of 25 for the failure case "Weld initiated Fatigue fractures" with the following description:-

> "Weld initiated Fatigue fractures. Thermal, Transformation, operational stresses from welding initiate cracks in weld material or base material especially if material is hardenable due to fast cooling to Martensite. Welding heat removed quickly in large and cold materials. Problems also increased by

poor construction, poor design, welding patches/patch, and other weld deposits"

The next closest matching case is "Keyway failure due to high hardness of surface and high stress cycles" with a score of 22 and has the following description:-

"Keyway failure due to high hardness of surface and high stress cycles, Keyways have small radii. This can lead to stress concentrations and high Kt, Kf values. Also, surface defects in that area can also lead to fatigue failure"

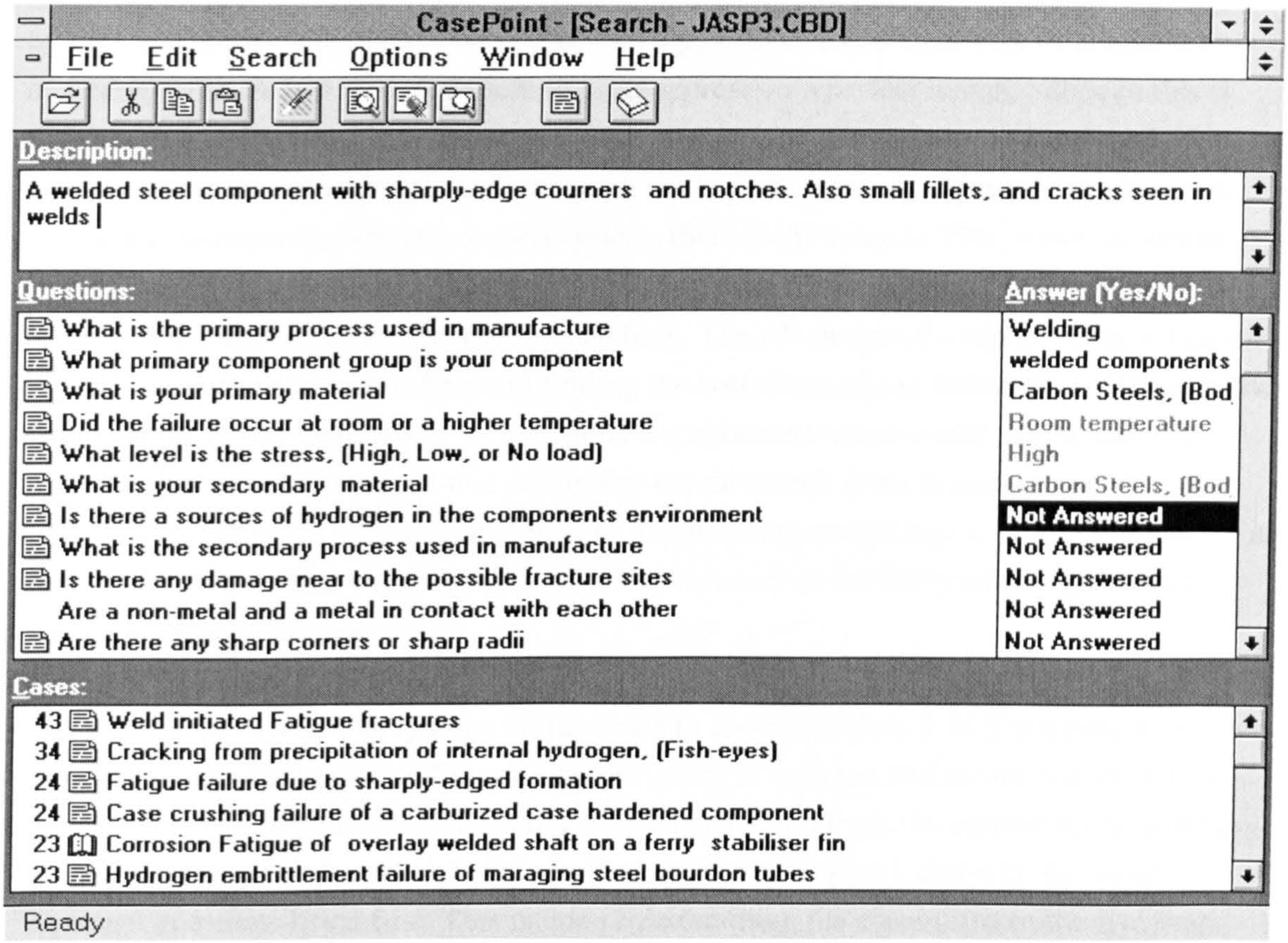


Figure 7.1. A typical example of search description with its effect on the questions and matching cases.

A typical example of a search description is illustrated in Figure 7.1 above. It shows how the keywords (welded and steel) within the description (A welded steel component with sharply-edge corners and notches. Also small fillets, and cracks seen in welds) have, via the programmed rules, answered the first three questions, indicated in the figure in bold.

7.2 Answer Questions

The question stage presents a menu of questions to the consultant/student to elicit more information specific to the failure problem. A menu of up to fifty questions is generated, the questions depending on the information given in the description. A hypertext browse facility is used to obtain more information on the questions (Figure 7.2). The description and questions are stored as a search case and this is compared with the stored cases. Hence, a numerical similarity score (1 to 100%) is developed by summing the score for the correct answers and subtracting the mismatch scores for incorrect answers between each stored failure case. Thus each stored case is matched against the search case with its resultant a matching score. A 100 percent matching score represents a perfect match, although this is unlikely especially with the increasing complexity as the expert system is developed. Hence a value below this is consider a match in which the expert system can stop asking questions. Through experience in using the expert system, this cut off value is 75%, however further work is required to assess the impact of this value and whether it is idea. It is believed that a higher value might be more accuract in matching. The advantage of a higher value is that the expert system has more of a chance in finding the correct matching failure case. However the disadvantage is that many different questions are answered which could match many un-related failure cases. To reduce this possibility the mismatch score is much lower that the match score. However, further adjustment to the matching weightings scores will allow for an increase in the off value which will increase the accuracy of correctly matching the search case to a stored failure case.

The expert system will supply a list of questions to answer (Figure 7.1). Each time a question is answered (shaded in gray in Figure 7.1), the search is updated and so the existing list of questions are rearranged and additional questions generated from the current list of matching cases. Each question appears only once in the list (no duplication), and with the most important questions listed first. This is done by examining the current list of the five best matching cases and using the questions associated with these cases. However, the questions

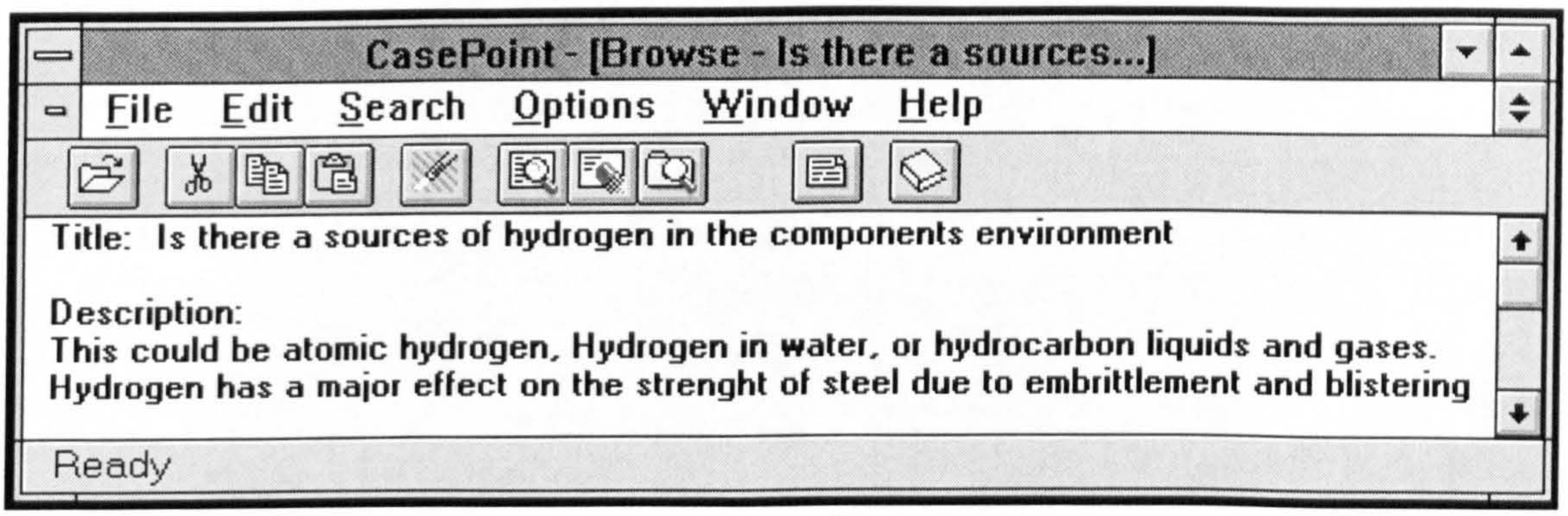


Figure 7.2. Illustrating typical hypertext question browse.

may be answered in any order, and answering all the questions listed is also not necessary. The user simply supplies the information that is available. Answering a question and searching again serves to differentiate cases from one another. This quickly narrows down the field of possibilities. An example is illustrated in Figure 7.1 above where the next question to be asked is "Is there a source of hydrogen in the component's environment".Its position in the list relates to its pivotal role in deciding whether the matching case is either "Weld initiated Fatigue fractures" or "Cracking from precipitation of internal hydrogen, (Fish-eyes)", i.e. the latter failure mode requires hydrogen for its initiation. If the user requires more information on this question then the hypertext browse facility could be used as shown in Figure 7.2.

Following each search the first few matching cases are usually very similar to the previous list but with revised match scores. Typically, one or more of the cases will show an increased score, while the scores of other cases may have diminished. Note that in Figure 7.1 the first two cases are at least 10 points above the other cases after the answering of six questions. Some cases may be eliminated entirely, permitting other cases to take their place in the "top five." This results in a new list of questions to answer. The user continues to answer questions and the search continues until one case shows an acceptably high score, or until all pertinent questions have been answered. Then the user browses the "winning" case(s) and their

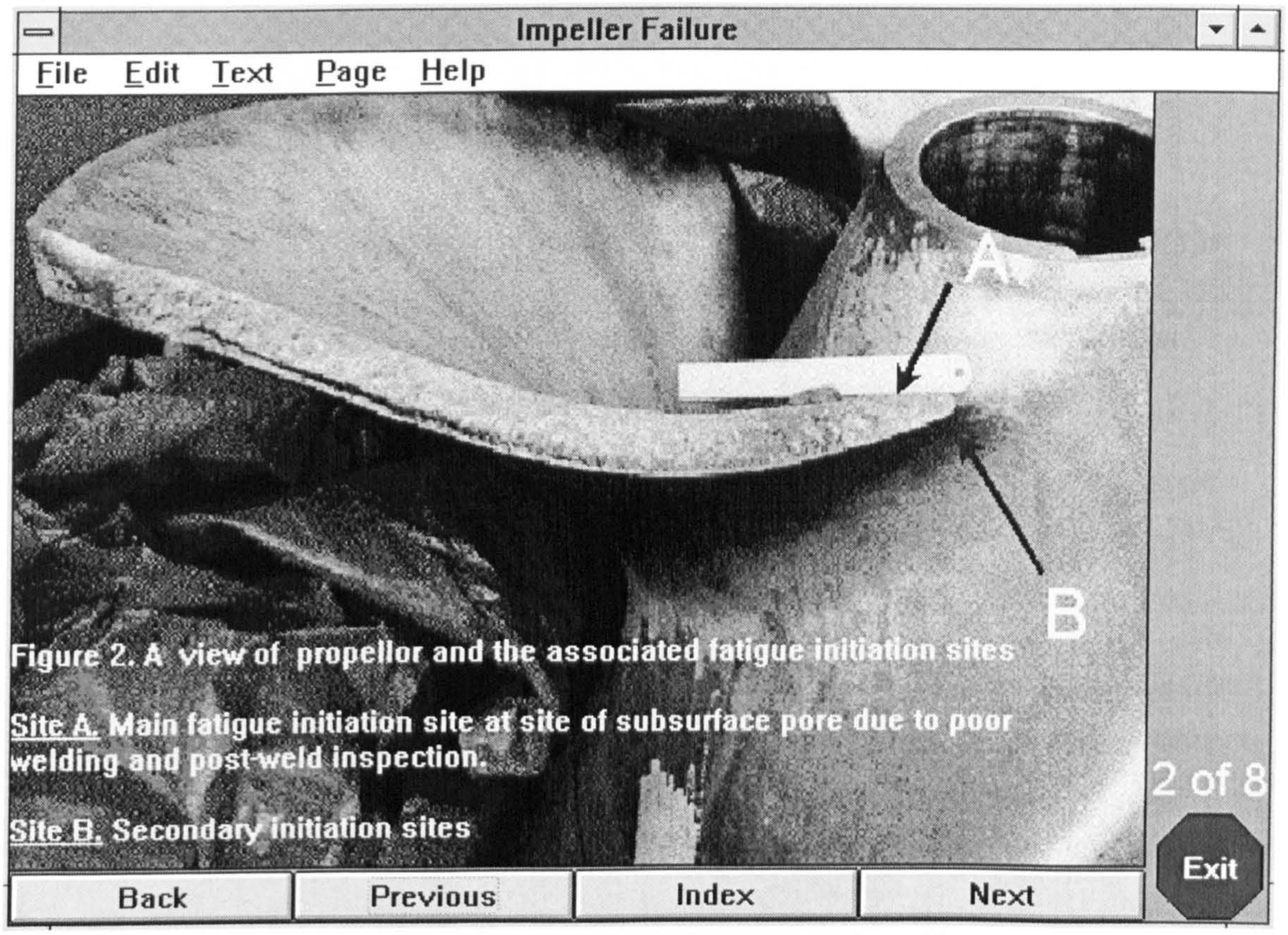


Figure 7.3 Multimedia application detailing the failure at a repair weld on a ship's impeller due to fatigue.

recommended actions.

Sometimes questions will be seen in the list that do not seem pertinent to the current case. These can be ignored, and other questions can be answered instead. The reason for these questions is that the matching algorithm can produce false hits in certain cases, particularly if the search description was vague or very short, or if the case based system happens to be very small. There is no penalty associated with leaving a question unanswered. However, the generation of a question not pertaining to the current case does reduce a user confidence in the expert system. Methods of rectifying this are discussed in chapter 18, on further work.

If questions are not understood by the user, then the program, provides a means to browse additional information about a question by simply double-clicking the mouse on the question or its icon. This reveals either a scrolling text field or a hypertext graphical presentation to display a full explanation to help answer the question (Figure 7.2). The hypertext browsing facility is used to elicit more information on the questions, cases, and solutions. The hypertext facility develops intelligent links between other media documents such as graphical images, formulae and calculating facilities, references, and real failure case histories. The graphical presentations could be either a Toolbook application or a World Wide Web pages. These are shown in figures 7.3 and 7.4 and are further discussed in section 12. Marking a question "Not Answered." is also always possible.

The Answers field responds in one of four ways, depending on what type of answer is expected: Yes or No; List; Numeric; Text.

Yes or No questions are answered by means of a dialogue box containing buttons for Yes, No, and Not Answered. Alternately, a faster method is simply to highlight the answer using the arrow keys, then set the answer in one step using Y for yes, N for no, and T for not answered. This method bypasses the dialogue box for a faster throughput.

List answers cause a dialogue box to pop up containing a scrolling field of legal answers. Simply click the mouse on the answer preferred, and click on the Answer button to confirm. This selects the answer and dismisses the box.

Numeric answers causes a dialogue box to pop up for user input. This box accepts numeric values only, and enforces a maximum and minimum value limit on each question. Just type in the number and press the Enter key to input the number and to dismiss the box. The numeric answer will appear in the scrolling answer field.

Text answers cause a dialogue box to pop up containing an editable field. Unconstrained text may be typed in this field. The enter key is pressed when typing is complete to input the data and to dismiss the box.

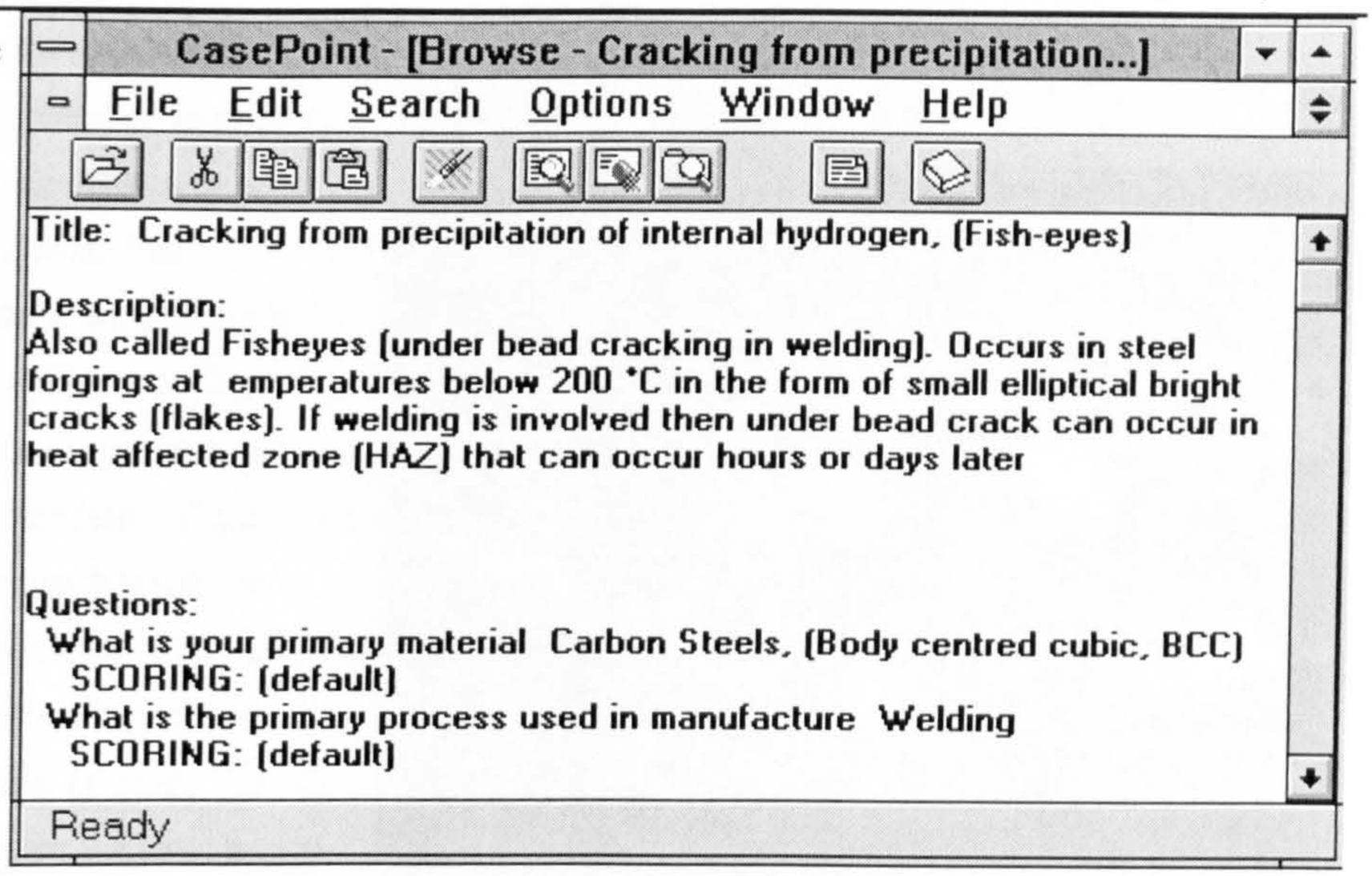


Figure 7.4. Illustrating typical browse of a failure case text.

7.3 Choose cases

The failure analysis expert system now displays the list of cases as the output of the search (i.e. description entered and questions answered). Other situations might require recommended actions to the cases. The Search Panel accommodates both perspectives by letting the user toggle between a display of cases and a display of actions associated with those cases. The similarity matching algorithms list the cases in the knowledge base according to the similarity with the search case, the greater the similarity, the higher the matching scores. The consultant now chooses the highest matching case or browses through other cases matched with lower scores which may be more applicable to the problem as there may be more than one "answer". This is not a common facility that is available in most rule based expert systems, which generally only provide one "answer".

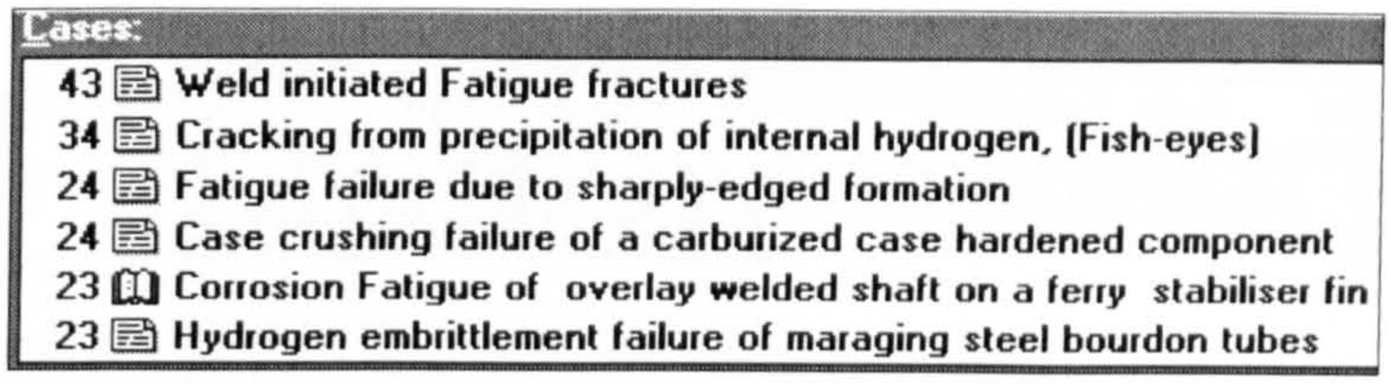


Figure 7.5 Detail from figure 1 of the matching cases.

The information the cases provide is sufficient to solve practical diagnosis problems. Thus, in a few minutes a short, clear, quick and concise description of the possible failure mechanism is revealed. However this failure mechanism might not be the failure mechanism expected by the consultant, and yet from the information given, it might be just as correct. Before any information is entered, all the different cases stored are equally possible. Hence all failure mechanisms are equally possible. As more information is entered (i.e. questions answered), the possibility of all the failure mechanisms being relevant is reduced. However entering all the information required to single out a given failure mechanism is not generally possible,

especially when the information entered is unlikely to be that accurate. For example, knowing with any real accuracy the stress levels, the environmental pH, and the material composition is very difficult. Thus the consultant is made aware of various possible failure mechanisms. Figure 7.1 illustrates a typical search with the resultant selection of cases (Figure 7.4). In selecting a case either a graphic multimedia application (Figure 7.3) or a section of text (Figure 7.6) is shown. Figure 7.6 illustrates a typical browse of a failure case text. The description in figure 7.6 is the section of text used in matching with the search description, and is used to describe the case when browsing for more information. Additionally, there are the questions and actions that are related to the case. The questions are listed with their title and the weighting scoring, whereas actions are just listed. A full listing of the text from all the cases is given in chapter 8.

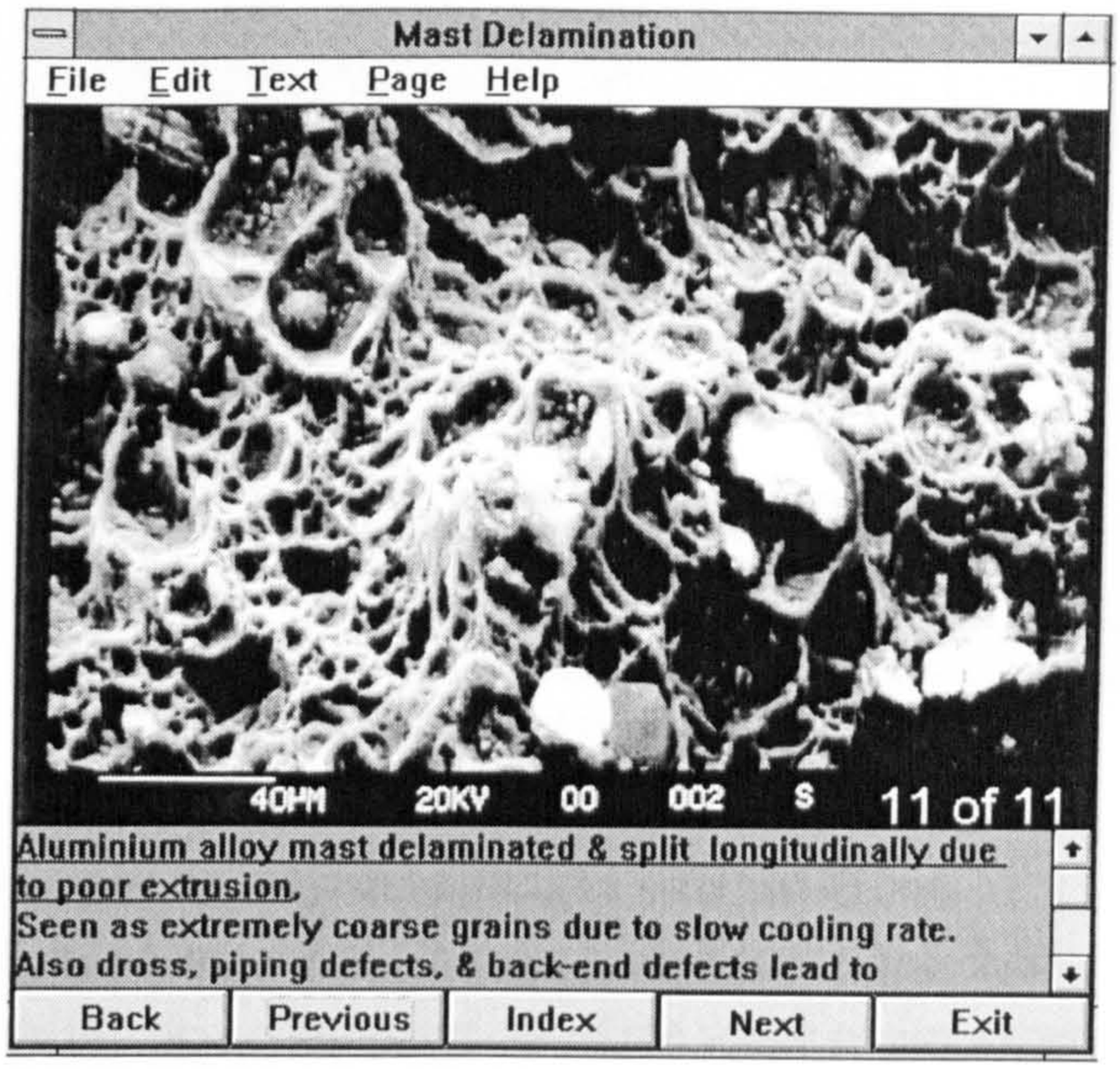


Figure 7.6 Multimedia application for the delamination of an extruded aluminium mast.

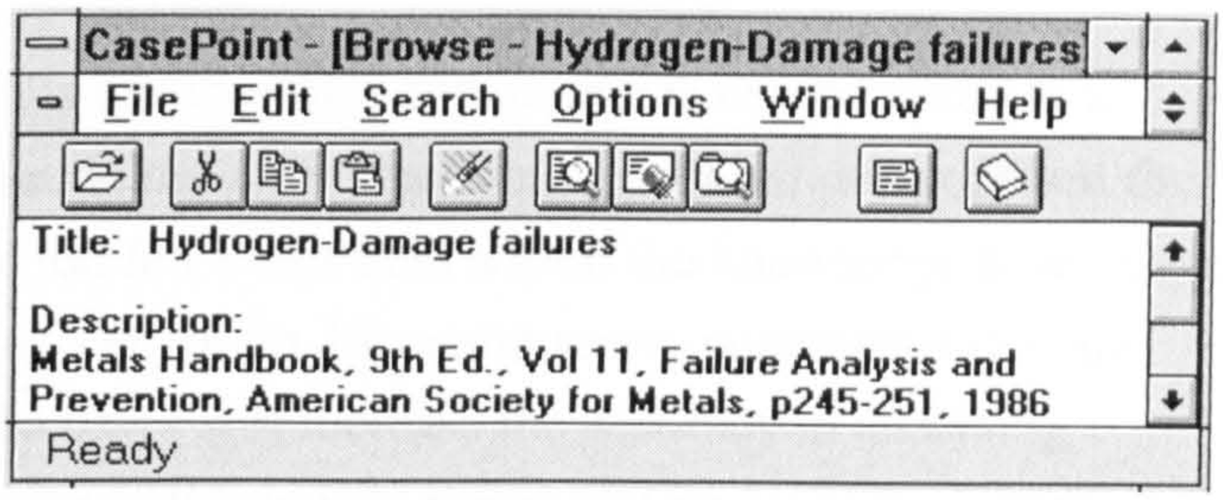


Figure 7.7 Reference as a simple action text.

7.4 Selecting actions

In this expert system, an action is a remedial solution to a failure problem. Human experts are not reticent about identifying actions. The actions are usually the part of the case that they can describe most clearly. In fact, the classic problem with human experts is that they can tell exactly what to do, but have trouble explaining how they decided to do it (see chapter 4). In a more general application, an "action" may be thought of as a convenient data record that associates additional information with the case. For instance, in the expert system, "Delamination and longitudinal split in extruded aluminium alloy mast" is a part of the class of actions represented by the case "Delamination and longitudinal split in extruded aluminium alloy mast." This failure mode is represented by a case, and additional information about the condition is stored in action records (Figure 7.6). These action records are displayed in either a simple text format that states a simple reference (Figure 7.7) or a more comprehensive description (Figure 7.8) in a multimedia electronic book, (Figure 7.8). Many actions are not

always totally case-specific in that cases may share actions. For instance the action related to "Spalling problems" will be attached to several cases in which spalling may be a problem. Spalling occurs after surfaces have been brought together under a repetitive load in which the sub-surface shear strength is inadequate to withstand the shear stress to which it is subjected. This could be via a forge, a rolling mill, or hammering, etc. It can be seen that many cases could be linked with spalling, to which there is a common answer. Cases such as "Impact spalling in steel" and Case crushing failure of a carburized case hardened component". In most cases and actions, there are references related to further reading, as full descriptions are out of the scope of any expert diagnostic system. For example Spalling occurrence is explained in Zener and Holloman, J. Appl. Phys., Vol. 15, 1944, p22.

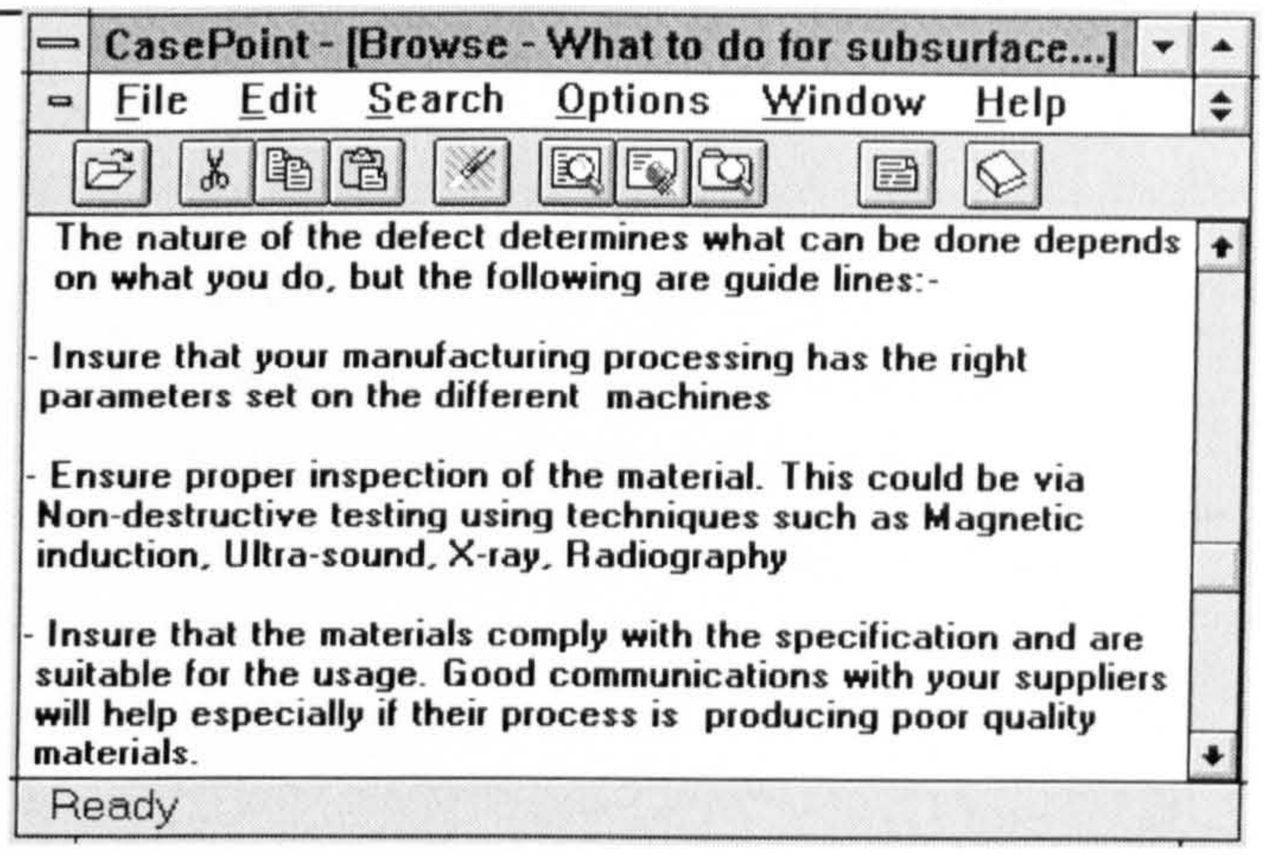
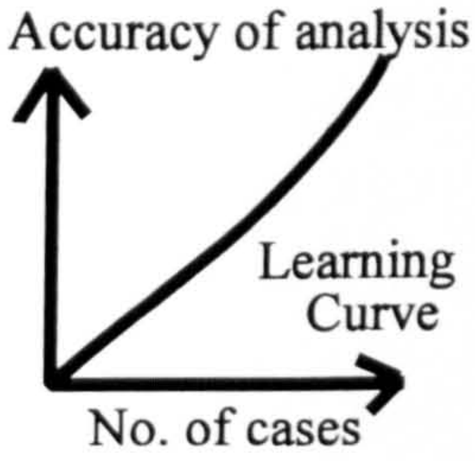


Figure 7.8 Action with detailed text.

7.5 If the search is unsuccessful

Sometimes a search on a failure problem is unsuccessful and no match can be found to a similar failure case in the knowledge base. In the early stages of case based development this is normal and to be expected as there are too few cases held within the knowledge base. Case bases go through a "learning curve" just as people do, by continuously accumulating extra cases for the knowledge base. These extra cases will increase the accuracy in analysing searches and matching these to similar cases. Within this expert system cases have been added relating to their commonly assumed occurrence and their occurrences in the literature as detailed in chapter 15 on datamining and chapter 8 on the development of the different cases. However, there may be many practical failure situations that the knowledge base author was not able to predict and thus write cases for the knowledge base. These unsuccessful searches can be logged by the expert system as an unresolved case.



This is done by a mouse click on the Unresolved Search button at the bottom of the Search Panel. It makes a copy of the current state of the Search Panel and stores it. These copies may be stored directly in the case based system or as a text file.

During future evaluations, a failure analysis consultant can then investigate the unresolved case from the description saved by the expert system, and produce a revised case. This is further detailed in chapter 11.

Chapter 8 The development of cases

8.0 Introduction

This chapter examines the methodology and cases used within the expert system. First the scope of possible failure mechanisms is examined and analysed to established how many failure mechanisms are to be included within the expert system. The relevant failure mechanisms are listed and finally the resulting expert system cases are detailed.

8.1 What are the main engineering failure modes?

In the initial development of the expert system the question of breadth of materials to be included was left open. However it became clear, early in the work, that to include industrial materials other than metals would be problematic, due to the amount of information required by both the expert system and the knowledge engineer. Although ceramics, plastics and organic (wood, paper, wool, etc.) materials would not be included within the first prototype, design considerations for the future additions of these classes of materials were considered.

Thus, within the scope of this thesis only the failure of components made from metallic material was considered for the expert system. This is both large enough to take into account the complexity of the problem and yet small enough to be manageable at the present time. In future modifications and developments of the expert system other materials could be added. However, this would be after the development of a generic formalized model of the failure analysis process.

In practice the Expert system needs to distinguish between an estimated 150 different mechanisms (subsets of modes) of failure (ASM Metals Handbook 1986). One hundred and twenty of the main failure mechanisms are listed in section 8.2. Some failure mechanisms are linked to two different modes, for example corrosion fatigue, creep fatigue. Although considering these as a separate mode of failure would be possible, an expert would diagnose the situation as either a corrosion problem that has initiated fatigue or a fatigue problem that has worsened due to corrosion.

Failure mechanisms have been separated into different associated failure modes depending on their salient features (physical, mechanical, or chemical interactions or effects). Some failure modes are normally considered separate, as they are not associated with any other failure mode or mechanism. Further details of these divisions and associations of failure modes and mechanisms are given in chapter 4.

8.2 The different failure modes and mechanisms in the expert system

Key:- Number relate to case numbers,

Over-load failure (general 22)

Ductile fracture (29)

Ductile flat face tensile fracture (73)

Ductile shear face tensile fracture (74)

Transgranular brittle fracture

Intergranular brittle fracture

Ductile to brittle transition failures

Temper embrittlement (350-600°C, 54)

Radiation embrittlement (55)

Brittle fracture due to strain-age embrittlement in a mild steel hook (63)

Impact\shock loading failure

(Tensile shock overload on carbon steel cable 16)

(Impact spalling in steel 25)

(Tooth-bending impact and shear failure of gears, 40)

(Tooth chipping of gears, 41)

(Impact failure induced by water hammer on a welded pipe, 83)

Case crushing failure (of carburized case hardened components, 42)

Other types of overload failure

(Overload failure in sand cast Al-alloy 21)

(Internal stress rupture in a gear tooth, 38)

(External stress rupture in a gear not in service, 39)

Fatigue fracture (General, 7)

Fretting (75)

Unidirectional- bending

Torsional (35)

Reverse bending

Rotational bending

High cycle (casting, 32)

Low cycle (steel 17)

At elevated temperatures

Thermal fatigue (of gears, 43)

Contact Fatigue

Surface-pitting fatigue (in gears 20)

Subsurface cracking

Corrosion fatigue (28)

Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin (59)

Fatigue fracture due to processing

Initial manufacturing defect led to fatigue (2)

Processing induced fatigue in Al alloy component (18)

Subsurface defect leading to fatigue in critically loaded part (19)

Fatigue fracture due to the influence of metallurgical factors

Internal discontinuities, such as porosity, shrinkage, gross non-metallic inclusions, cracks and voids.

Fatigue fracture due to design

Fatigue failure of spring (11)

Keyway failure-high hardness and stress (12)

Fatigue failure due to keyway (13)

Fatigue fracture due to abrupt thread run-out (58)

Stress corrosion cracking, SCC (Materials related to corrosion medium)

Austenitic stainless steel (austenitic chromium nickel steel 14) (300 series 24)

Maraging steel

Ferric Stainless steel (part resistant to SCC)

Low and wrought carbon steel alloys

Al Alloy (4)

Copper alloys

70% Cu, 30% Zn, (3)

Magnesium alloys(resistant to SCC with high Mg %)

Nickel alloys (Very resistant to SCC with high Ni %)

Gold (5)

Titanium alloys

Embrittlement by liquid metal

Copper alloy (Brass, 30)

Steel (31)

Embrittlement by solid-metal environments

Hydrogen damage

Hydrogen embrittlement (Maraging steel bourdon tubes, 33) (63)

Hydrogen induced blistering (64)

Cracking from precipitation of internal hydrogen (65)

Hydrogen attack (66)

Hydrogen cracking from hydride formation, (Titanium 67)

Elevated temperatures failures

Creep and stress rupture

(Creep failure of a superheated parts (tubes) by graphitization/spheroidization 27)

Thermal fatigue, see fatigue (in gears, 43)

General oxidation, and exceeding normal operating temperature

Carburization (stainless steel only) (decarburisation, 52)

Metal dusting (480 to 815 °C up to 1095°C reducing atmospheres)

Corrosion fatigue, see fatigue (28)

Distortion failures

Buckling (76)

Gross yielding, overloading (22, 29)

Incorrect or failure to meet specification

Faulty heat treatment

Warping

Faulty case hardening

Faulty repairs

Elastic distortion

Ratcheting, can lead to ductile or low cycle fatigue failure

Caustic embrittlement

Caustic cracking due to poor rivetted seams in a steel ships' boiler (58)

Wear failures

Adhesive wear (gears, 37)

Abrasive wear

Wire wooling of shafts

Fretting

Fatigue (75) and fretting wear

Friction

Lubrication failures

Erosion wear from solid particles (in pipes 15)

Flow erosion (in pipes 23)

Liquid erosion failures or cavitation erosion, also see wear and corrosion

Corrosion failures

Uniform corrosion (general, 44)
Pitting corrosion (47)
Selective leaching
Dezincification (49)
Denickelification (49)
Graphitic corrosion
Intergranular corrosion (48)
Selective attack on inclusions
Concentration-cell corrosion
Crevice corrosion (6) (46)
Differential-temperature cells
Galvanic corrosion (45)
Liquid velocity affected corrosion, see liquid erosion failures
Erosion corrosion
Impingement corrosion
Cavitation erosion
Bio-fouling and bacterial corrosion (Biological corrosion, 53)
Anaerobic bacteria
Aerobic bacteria
Corrosion in water containing fuels
Marine fouling
Buried metal corrosion
Atmospheric corrosion
Gaseous corrosion in 300 series stainless steel (80)

Sour-gas environment failures

Sulphide-stress corrosion cracking (34) (50)
Hydrogen-induced (pressure) cracking (51)
Stress corrosion cracking see SCC

Welding and other rapid heating process failures

Weld initiated fatigue (8)
Contact corrosion, welding with more or less noble electrode (10)
Brittle fracture of a rail arising from flame-cutting (57)
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin (59)

Other processing type failures

Incorrect grinding (1)
Cracking on the parting line of closed-die forging (26)

Excessive wear in single sprocket or **gear** (36)

Delamination and longitudinal split in extruded aluminium alloy mast (70)

Internal cracks in cast steel 9% Ni (81)

Other component type failures

Electrostatic discharge attack on a thrust bearing (82)

Brinnelling failure (77)

8.3 Case selection

To understand how, in the expert system, cases were developed it is important to understand how a case is selected from all the cases. The failure analysis expert system displays the list of cases and actions as the output of the search. The search panel accommodates both perspectives by letting the user toggle between a display of cases and a display of actions associated with those cases or a multimedia application, if applicable. The similarity matching algorithms list the cases in the knowledge base according to the similarity to the search case; The greater the similarity, the higher up the list. The expert can choose the case from the list. However the consultant/student does not have to choose the highest match but can also browse through other matches with lower scores which may be more applicable to the problem. This is not common in most expert systems in which only one "answer" is provided. However in failure analysis and component reliability, there may not be just one "answer".

8.4 Failure analysis knowledge organised into cases

So far the discussion has centred around the background work relating to expert systems and case-based reasoning with a few examples. The most complex and difficult stage is to organise the failure analysis knowledge into cases, action, and questions. Initially, this was done in an un-organised fashion that tested the capabilities of the software and showed ways in which the software could be improved. The next stage was to list the majority of the most common failure modes as detailed in section 8.2. These common failure modes were split into the following sub groups

Over-load failure
Stress corrosion cracking
Hydrogen damage
Corrosion fatigue
Caustic embrittlement
Corrosion failures
Sour-gas environment failures
Other processing type failures
Fatigue fracture(design, processing, metallurgy)
Embrittlement (liquid metal, solid-metal environments)
Elevated temperatures failures
Distortion failures
Wear failures
Liquid erosion failures or cavitation erosion,
Welding and other rapid heating process failure
Other component type failures

This had its problems, for example, in the subgroup, "Embrittlement by liquid metal " there is a real life failure case on the fatigue failure of a steel shaft which was initiated by molten bronze penetration. The problem is that the final failure was by fatigue, so should it go into the "fatigue" subgroup, or as it was initiated by the bronze penetration, should it go into the "Embrittlement by liquid metal".

Embrittlement by liquid metal

Copper alloy (Brass, 30)
Steel (31)
Fatigue failure of a steel shaft initiated by molten bronze penetration (64)

The conclusion was that the most important stage of failure was initiation because the initial crack, defect, or whatever determines the final outcome, which could be by many different types of failure, such as fatigue, overload, buckling, etc. The final outcome is secondary to the real problem so it was decided that whatever initiated the failure, whatever the outcome, then the failure would be placed into the subgroup related to the initial defect.

The sub-grouping of the different failure modes is important due to the similarity of certain groups of failure modes. i.e. stress corrosion cracking, failures involving welding, etc. This helped the author to keep track on the questions and actions. It was found that it was important to have the same type of question within a subgroup for the matching of the cases, so that all the cases within a sub-group are affected by a question or action.
If we wish to find a failure mode in a given case for which the solution is in a given action, then questions must be constructed. Thus when the programming was undertaken, first the cases are written then the action is considered and finally the questions that will link the two.

In building the cases, in a case based expert system, the case title and then a description has to be considered first. The case title is a one-line phrase that uniquely identifies the case. It is very similar to the title of a book or a report. The title should accurately identify the case by emphasizing the unique feature that makes the case important.

The title of a case becomes part of the case description for purposes of searching. This means that it is not necessary to retype information in the description field if it is already present in the case title. Infrequently, the title alone might be sufficient and no further description would be required.

The case description is a critical paragraph of text that, with the case title, forms the basis for the first search from the Search Panel. The object is to write a sentence or short paragraph that describes the symptoms of the problem, or the characteristics of the case, as the operator is likely to phrase them.

There are several things to keep in mind while planning the descriptions. One is to try to make the search descriptions all about the same length. This is not always possible, of course, but cases with long descriptions are more likely to contain text from the search description and therefore receive higher scores. Keeping the case descriptions about the same length in all the cases helps the expert system perform a more accurate initial search.

The only thing that can be done wrong in writing a case description is to load it with obscure terms that the expert system user does not know. This is not a problem for systems where the users will be a domain expert, but since the purpose of an expert system is frequently to distribute expert knowledge to non-experts, it is appropriate for the case-base author to be cautious about this issue. This can be cured by either converting the description into lay language as far as practicable, and by establishing a standard vocabulary for descriptions and training the operators to use it (See section 8.5). One of the main reasons for selecting CBR Express, as the expert system shell, is that it is very forgiving of the description given at either the development stage or the searching stage, but it is not perfect and it does not read the users mind. There must be some similarity between two descriptions before they can be matched.

Failure analysis is a very technical subject with it own terminology. It was therefore important to standardize the terminological descriptions so that all of the failure case history authors and users are "speaking the same language". This was done by using a “Thesaurus of Metallurgical Terms” (The Materials Information Society, 1992), but even with failure analysis terminology, some phenomena can have three or four different alternative words to describe the same thing (see section 8.5 and 11.1). However, the terminology used within the expert system has been so designed that they are words and phrases that the end user is most likely to use and this has been developed into its own Thesaurus of Failure Analysis Terms, as detailed in section 8.5.

These words and phrases have to be included within the case description One method, is to list the alternative terms after the main part of the description. For example:-

Brittle fracture, fast failure, snapped, shattered

Due to the matching algorithm for descriptions, a person searching for "fast fracture" would get a perfect match against this description, because both words occur in it. An equally good match occurs for "shattered in a brittle manner" and "snapped."

People tend to express themselves in relatively predictable ways, and that exhaustive efforts to include all possible expressions are unnecessary and generally impossible. An example of

this can be seen when someone tries to describe a fracture which they think might be fatigue. The description might read:-

"Possible fatigue failure of bolt"

This gives only a little information but the expert system has to include all the related terms, such as:- Bending fatigue, Corrosion fatigue, Thermal Fatigue, Torsional fatigue, fretting, etc. Since the description is really just another "context" question. It was found important to think of the description as a tool for creating similar groups of cases in the "question space." Therefore in the expert system, similar cases have similar descriptions so that the initial search can find them, whereas cases that have nothing in common have little overlap in their descriptions. As well as using keywords, phrases were used rather than sentences: This was done to keep text within the case description to the point. Also as the expert system discards many "noise" words anyway (see section 11.1), it is easer to focus on the more relevant phrases from the start. This helps the searches to be much more efficient.

Many expert systems are built by more than one author, and over time most expert systems will be updated and enhanced. It is hoped that further development will be undertaken on the failure analysis expert system over the next few years. Therefore to help with the tracking and evaluation of the information to be included, the author's initials and change dates should be included in the description. There is a very slight overhead in that the search will be slower, but it is still worth including. The precise format suggested by the author is to give the initials and date as follows:- (Initials-day Month Year) (XYZ-ddmmyy). An example appears below.

Case description: Brittle fracture, fast failure, snapped, shattered BGM-300998

It is also good practice to adopt a similar convention to record details when a case is modified. The approach here is to record details of the last time that a case was changed and to keep the information about who originally created the case, and when they did so. This should be done in the same format as described above. For example if the case has been altered several times, but most recently by a case author called PJGJ on 4th December 1998:

Case description: Brittle fracture, fast failure, snapped, shattered low impact strength, low notch strength BGM-300998 PJGJ 041198

Recording the details of changes should also be done on actions and questions, especially where the cases, actions and questions are either being built or altered by someone other than the expert, or the knowledge is coming from more than one such expert. It may in the future be wise to record the source of each case again using a set of initials.

8.5 Thesaurus of failure analysis terms

In the following table a typical term that could describe the nature of a failure is followed by the hierarchal structure based on work by The Materials Information Society(MIS, 1992). From this, using the author's own knowledge and other sources (MIS, 1992) (Roget Thesaurus) and (Collins Thesaurus) alternative and related terms and the definition of the resulting failure outcome are listed. This list does not claim to be comprehensive in any manner. However it does illustrate the multiple terms that could be used to describe a failure. This is a considerable problem which needs to be taken into consideration when developing cases, actions, questions, and rules. Thus suitable alternative and related terms were associated with failure cases in the database and the possible results were used to develop questions. For example question 58 "Is the failure just surface damage or has it broken into parts", relates to many different failure mechanisms such as seizing, wear, wasting, discolouring, creep, deformation, fractures, delamination, ruptures, etc. Another example is question 59, "Has spalling or delamination of the surface occurred". On examining the table below, many more such associations could be made. However to associate too much means nothing is disassociated, so a delicate balance has to be made.

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Seized (Seizing)	Properties- Mechanical properties- wear- adhesive wear-	Seizure, Jammed, Fused	Abrasion, Binding, Expansion, Friction, Galling, Pitting (wear), Rubbing, Scoring, Scuffing Shrinkage	Unwanted joining of parts
Penetrated		Holed, Breached, Pierced, Punctured, Perforated, Pricked, Permeation	Absorption (materials), Dialysis, Diffusion, Dispersing, Gas alloying, Impregnation, Infiltration, Leakage, Osmosis, Percolation, Permeability, Piercing, Saturation (colour, magnetic), Seepage, Transpiration, Vulnerability (Permeation)	Localized, through-thickness defect
Wear	Properties (attributes), .Mechanical properties, ..Wear, ...Abrasion, ...Gouging abrasion, ...Grinding abrasion, ...Scoring, ...Abrasive wear, ...Cutting wear, ...Adhesive wear, ...Galling, ...Scoring, ...Scuffing, ...Seizing, ...Case crushing, ...Catastrophic wear, ...Corrosive wear, ...Deformation wear, ...Erosion, ...Abrasive erosion, ...Brittle erosion, ...Ductile erosion, ...Erosion-corrosion, ...Liquid impingement erosion, ...Fatigue wear, ...Frictional wear, ...Hot wear, ...Impact wear, ...Pitting (wear), ...Thermal racheting, ...Welding wear,	Attrition, Cratering wear, Mechanical Wear	Ablation, Abradant, Antifriction, Anti-galling, Damage, Detrition, Durability, Fretting, Friction, Hard surfacing, Hardness, Rubbing, Spalling, Surface finish, Tool life, Tribology, Wear resistance,	Damage to a solid surface due to the relative movement between a surface and a contacting surface or substance, causing loss of material.
Wasted		Degraded, Worn, perished,, decayed,	Corroded, Crumbled, Faded Consumed, Spoiled, Spoilt, Ruined, Withered, Dwindled, Declined	Loss of material

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Pitting (Mechanical Wear)	Properties (attributes), .Mechanical properties, ..Wear, ...wear	Cavity, Cratered, Hollowed, Dented, Indented, Pocked,	Abrasive Erosion, Abrasive wear, Fretting, Galling, Impingement erosion, Scoring, Scuffing, Seizing,	Localized mechanical surface attack
Pitted (corrosion)	Degradation, .Corrosion, ..Concentration cell corrosion, ...Pitting corrosion, ...Etch pitting,	Cavity, Cratered, Hollowed, Dented, Indented, Pocked, (Pitting potential)	Anodic protection, Cathodic protection, Chemical attack, Corrosion cell, Galvanic corrosion, Humidity, Passivity, Rusting,	Localized chemical surface attack
Discoloured		Faded, Colouring, Staining, Tarnishing, Decolouring (bleaching)	Colouring, Damage, Degradation, staining, Tarnishing,	Transformation of surface
Cracking (fracturing)	Fracturing, .Cracking (Fracturing), ..Crack closure, ..Crack initiation, ..Crack propagation, ..Stress corrosion cracking, ..Stress cracking,	Split, Fatigue cracking, Hot cracking	Breaking, Failure, Tearing, Weld defect	Producing a narrow opening without coming apart
Cracks	Defects, Cracks	Crevices, Fissures, Veining	Cracking (fracturing), Crazing (Ceramic coatings, Crack propagation, Enamelling), Flakes (defects), Fractures, Holes	A narrow opening in a part
Creep (materials)	Properties (attributes), .Mechanical properties, ..Creep (materials), ...Creep life, ...Creep rate, ...Creep recovery, ...Creep rupture strength, ...Creep strength	Plastic flow, Creeping	elasticity, Cold flow, Deformation mechanisms, elasticity, Flow, Inelastic, Plasticity, (Creep limit and properties)	Time dependent strain occurring under stress

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Damage	Damage, .Radiation damage, .deface, ..mutilate		Decay, Decomposition, Defects, Degradation, destruction, deterioration, Discolouration, Disintegration, Durability, Erosion, Flooding, Fractures, Radiation effects, Strains, Warpage, Wear, Weathering ruin, weaken, wreck, spoil, accidental damage,	Reduction in usefulness, or appearance
Decomposition	Decomposition, .Decay, ..Radioactive decay, ..Weld decay, .Phase decomposition, ..Eutectic decomposition, ..Eutectoid decomposition, ..Spinodal decomposition.		Damage, Decomposition reactions, Degradation, depolymerization, Destructive distillation, Deterioration, Digestion, Disintegration, Dissociation, (Decomposing)	To separate into more stable elements
Defects	Defects, .Casting defects, ..Blowholes, ..Pipes (defects), ..Scabs (defects), .Cracks, .Crystals defects, .Disclinations, .Inclusions, ..Nonmetallic inclusions, .Rolling defects, .Surface defects, ..Flakes (defects), ..Orange peel, ..Scabs (defects)	Aberrations, Flaws, Imperfections	Damage, Fractures, Holes, Nonmetallic inclusions, Seams, Segregations, Voids	An imperfection . A sub-standard point within a substance.
Deflection		Elastic stressing	Bending, Bowing, Camber, Curvature, Deformation, Deviation, Diffraction, Dispersing, Displacement, Distortion, Divergence, Extension, Flexing, Reflection, Refraction, Sag, Strain, Torsion	Elastic deviation from a set shape and back to the same shape

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Deformation	Deformation, .Elastic deformation, .Plastic deformation, .Prestraining	Cold deformation, Deforming, Hot deformation	Bending, Bowing, Buckling, Camber, Creep (materials), Curvature, Damage, Deflection, Dislocations, Displacement, Distortion, Elasticity, Extensibility, Failure, Flexing, Fractures, Indentations, Plasticity, Sag, Strain, Torsion, Twisting, Warpage	Plastic deviation from a set shape to another shape
Degradation	Degradation, .Corrosion (see Corrosion)		Chemical attack, Curing Decay Decomposition, Depolymerization, Deterioration, Discolouration, Durability, Erosion, Failure, Fouling, Oxidation, Radiation effects, weathering	To separate into more stable elements
Fractured		Broken (Break), Sheared, Cleaved, Shattered	Breach, Rupture, Break, Fissure, opening, rift, gap, split, Crack, Cleft	Increased number of pieces, to increase the surface area of the component
Deformed		Bent, Distorted, Wrinkled, Bulged, Swelling, Protrusions, Creased, Ridge	Bowed, Deviating, Twisted, Warped, Distorted, Bent, Curved, Askew, Aslant, Uneven, Mutilated, Buckled, Contorted, Disfigured, Crushed,	Change of shape
Scratched		Furrowed, Grooved, Ditched Trench, Trough, Gouged	Abrasive wear, Scratch hardness test	Surface blemish
Delaminating	Failure, .Delaminating	Peeling, Delaminated	Laminating, Stripping (peeling)	Separation of layers

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Corroded	Degradation, .Corrosion, ..Atmospheric corrosion, ..Bacterial corrosion, ..Carburization (corrosion), ..Concentration cell corrosion, ...Pitting (corrosion), ...Etch pitting, ..Crevice corrosion, ..Demetallization, ...Dealuminization, ...Dechromization, ...Decopperization, ...Dezincification, ..Erosion-Corrosion, ..Exfoliation corrosion, ..filiform corrosion, Fouling, ..Fretting corrosion, ..Galvanic corrosion, ...Stray current corrosion, ..Hot gas corrosion, ..Preferential attack (corrosion), ...Intergranular corrosion, ..Rusting, ..Stress corrosion, ...Corrosion fatigue, ..stress corrosion cracking, ..Sulphurization, ..Tarnishing, ..Transgranular corrosion, ..Underground corrosion, ..Uniform attack, ..Weathering, ..Weld decay	Dissolved	Activation, Anodic protection, Biological effects, Cathodic protection, Cavitation erosion, Chemical attack, Corrosion cell, Corrosion mechanisms, corrosion products, Corrosion wear, Deterioration, Electrochemistry, Environment, Hydrogen embrittlement, Oxidation, Passivation, Protective coatings, Reactions (chemicals), Shelf life	Transformation of material
Melting	Liquefication, .Melting, ..Contact melting, ..Direct melting, ..Electric arc melting, ..Electron beam melting, ..Induction melting, ..Laser melting, ..Multistage melting, ..Oxygen melting, ..resistance melting, ..Vacuum (arc, induction) melting	Air melting, Fusion, Remelting, Thawing, Over heating, loss of coolant	Ablation, Alloying, Casting, Electro slag refining, Extractive metallurgy, Fluidizing, Fluxing, Foundry practice, Freezing, Fusibility, Heat of fusion, Open-hearth process, Pouring, Slagging, Tapping	Transformation of bulk
Exploded		Blasting, Combustion	Detonation, Fires, Shock waves, (Explosive Joining, Bonding, Welding, Cladding, Forming, Hardening, Plating, Impact testing)	Total destruction (or joining, and other surface effects, melting)

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Imploded	Failure, .Implode	Collapsed, Crushed		Total destruction
Ruptured	Failure, .Rupturing	Split, Divided, Cleft, Break, Burst, Split, Rip	Explode, Blast, Creep rupture	Burst or Break open
Breaking	Failure, .Breaking		Breakdown, Bursting, Chipping, Comminution, Cracking (fracturing), Crushing, Cutting, Fracturing, Fragmentation, Spalling, Splitting	To separate or cause to separate into pieces under a blow or strain, thus become inoperative
Buckling	Failure, .Buckling		Bending, Bowing, Distortion, Kinking, Torsion, Twisting, Warpage	A distortion caused at a critical compressive stress in a bar, beam, column, plate or sheet material.
Bursting	Failure, .Bursting	Break	Breaking, Fracturing, Fragmentation, Modulus of rupture, Splitting	To force open by internal pressure
Fatigue	Failure, .Fatigue, ..Bending fatigue, ..Corrosion fatigue, ..High cycle fatigue, ..Low cycle fatigue, ..Thermal fatigue, ..Torsional Fatigue, ..Rotational fatigue, ..contact fatigue	Fatigue cracking, Fatigue fracture, spalling	Crack initiation, Crack propagation, cycle ratio, Fracture point, Fracture testing, Fretting, High and low Temperature tests, Notch sensitivity, Prestressing, Rolling contact, Shear test, Shot peening, Stress concentration, Stress cycle, Stress ratio, Surface finish, Thermal stresses	Fracture due to variations in stress lower than tensile strength of material

Nature of failure	Hierarchal structure based on the Materials Information Society 1992 (MIS)	Alternative terms	Related term	Result
Break down (electrical)	Failure, .Electrical, ..Short-circuit, ..Electrical breakdown	Electrical breakdown , Short circuit	Electric arcs, Electric circuits failure	The unwanted passing of electrical current through a medium

8.6 Details of different cases

This section is extremely extensive, detailing over 75 cases in which during a search the expert system compares the search description and matches the questions against the database. The format states the beginning of the cases and its number; the title and description; followed by the associated questions with the ideal answer and its relative scoring (- or + or ± or default) This scoring permits the expert system developer to declare Yes/No and List questions as used in the current case to have "absolute" scoring behaviour. Text and Numeric questions are not used in the expert system partly because absolute scoring is not available for Text and Numeric questions.

The different scorings mean the following:

Disqualifying (-) scoring: If the answer contradicts the one given on the Search Panel, then disqualify this case. This scoring has been found extremely useful in the development of the expert system, as there are some situations which mean that a case is totally irrelevant. For example if the material is not gold then it is very unlikely that the failure is related to Stress-Corrosion cracking in Gold alloys (Gold alloy is effected by $FeCl_3$, Acetic acid-salt solutions)

Confirming (+) scoring: If the answer matches the one given on the Search Panel, then give this case a score of 100. This confirms the case as the closest matching case. Within the expert system this scoring is not generally used because there are too many variable to consider that the answer to one question will make a case an ideal match to the search case. Excluding or disqualifying cases is a more accurate method of matching a search case to the database of cases as it suggests a selection of possible cases rather than just one or two cases. With further matching the number of possible cases reduces. This is better that finding one or two cases and then trying to disprove them and replace then.

Both (±) types: A case may have disqualifying and confirming scoring for the same question. This feature has not been used in the expert system due to the complexity of the knowledge.

Default scoring: This is the normal case scoring in which values for Absence Weight, Match Weight and Mismatch Weight are set within the options menu.

Absence weight is a global parameter that penalizes the scores of cases that do not contain all of the questions currently answered on the Search Panel. In other words, when answering a question on the Search Panel, this parameter will lower the score of every case that does not contain the question just answered. The normal default value for this parameter is zero. It would seem ideal to set this absence weighting to its maximum value (10) as this would remove many different cases. However, for this to be successful the knowledge would have to be highly structured and all questions would have to be related to all the relevant cases. This could be difficult, especially if different people develop other failure cases into the database and they did not associate all of the correct questions to cases. Thus, having a high absence weighting reduces the flexibility and fuzzy reasoning ability of the expert system. Hence, within the expert system at present the value has been set at the default value of zero, although this has been varied in development to assess the outcome.

The match weight is a parameter that defines the relative contribution of this question to the score of a case. It tells the expert system how much weight to give this question compared to the other questions that make up the case. However, changing the match weight of a question impacts the scoring behaviour of all the cases that use the question. Also, the changed match weight does not take effect in all cases until the case base is reindexed or edited and saved for each affected case. Reindexing the case base rebuilds the case-base matching index necessary to make retrospective changes in question scoring behaviour, such as altering the match weight, mismatch weight, or type of a question in all cases where it occurs. Reindexing is also required any time you change the lists of separators, synonyms, and ignored words that are used to filter text input to CBR Express. The actual match weight values have been set according to the importance a question has in diagnosing a failure mechanism. This is further detailed in section 9.4.

Mismatch weight is used for penalty scoring. Instead of increasing the score of all cases with the correct answer for this question (the role of match weight), the mismatch weight penalizes the scores of all cases that have this question but do not have the right answer. This field displays integer numbers from 0 to 100, with 5 or 0 as the normal default, depending on the type of question. The default mismatch weight for list and text questions is zero, whereas for 'yes or no' and numerical questions use a default value of 5. This is because the possibility of answering a question in error is greater with list and text questions. However, in a similar manner to the match weighting, the mismatch weighting is dependent on the question context, so within the expert system there are variations in the values between zero and ten. If either the question is inherently fuzzy (i.e. it is a list type question) or there is considerable chance

of answering the question incorrectly (e.g. the loading is cyclic and the user states it as steady state), then the mismatch value is either 0, 1, 2, or 3. However, if there is a direct question such as a yes or no type question and the answer required is well known, then the mismatch weight is higher (i.e. 7,8,9,10). Apart from knowing the question type and making a judgement relating to the type, making judgements, on what is commonly known and how a wrong answer will affect the diagnosis and thus what values to assign the match and mismatch weightings is very much dependent on the expert system's author and the diligence undertaken in investigating the affects. As failure analysis is extremely complex and unstructured, the value for the mismatch weighting was standardised at 2.

A case may have questions with conflicting absolute scoring methods. If there is a conflict, CBR Express will set the case score to 100. This situation represents an error in case design, and therefore is presented to the operator for attention.

Once all the questions and the appropriate scorings are listed, the relevant actions and dates related to the case creation Last update, and Last used dates are stated.
Finally the status of a case is defined. This has to do with its position in the stored failure case's life cycle, and whether or not the case is indexed for searching. A case can be present in the case base and yet not be available to the search panel. A case may have one of the following status levels:

Draft: A case definition that is not yet ready to participate fully in the case base.

Active: This case definition is available for matching on the Search Panel.

Archive: This case definition is obsolete, and is not available for matching.

Unresolved: This is a description of an unresolved search.

As this expert system is presently in the prototype stage the majority of the cases are active.

8.7 Expert system cases

CASE1, Title:- Incorrect grinding, presence of hydrogen, & fatigue in Ni, Cr, Mo steel
Description:- cracking in Nickel-chromium-molybdenum Steel, (35NCD16), is intergranular and consistent with the existence of high tensile surface stresses. Stresses result of damage produced during grinding of the surface prior to Hard chromium plating (plated). Cracking produced by the absorption of hydrogen during electroplating. Cracks led to growth of fatigue cracks Fatigue failure, Hydrogen embrittlement, Crack propagation, Struts, ,peening, Incorrect grinding. ASM Vol.2 History of F.A. pg7.

CASE2, Title:- Initial defect led to initiation of fatigue crack
Description:- The initial defect was caused during manufacture . This can be seen by a large initial defect.

CASE3, Title:- Stress corrosion cracking in 70% Cu, 30%
Description:- Failure by cracking under combined action of corrosion and tensile stress, either external stress or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium

CASE4, Title:- Stress corrosion cracking in aluminum alloys
Description:- Failure by cracking under combined action of corrosion and tensile stress, either external stress or internal stress or assembly stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. In an Aluminum alloy S.C.C can occur in NaCl solutions, Seawater, Water vapour, especially High strength Aluminum-zinc-magnesium type 7000 series.

CASE5, Title:- Stress corrosion cracking in gold alloys by FeCl3, Acetic acid-Salt Solutions
Description:- Failure of a Gold alloy by cracking under combined action of corrosion and tensile stress, either external stress or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. Gold Alloy effected by FeCl3, Acetic acid-Salt Solutions. This rare failure mode is seen in the microelectronics and jewellery trade.

CASE6, Title:- Crevice corrosion
Description:- Crevice Corrosion due to differential oxygen concentration cell corrosion, also called Poultice Corrosion referring to accumulation of moist or wet particles, Dust, Sand, at joint, crevice, interface, between two surfaces, under debris, under fasteners, Nuts & Bolts, rivets. Can occur with similar metals but more corrosive with dis-similar metals.

CASE7, Title:- Possible fatigue failure problem
Description:- Fatigue fracture-failure under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of the fluctuating stresses.

CASE8, Title:- Weld initiated fatigue fractures
Description:- Weld initiated Fatigue fractures. Thermal transformation and cyclic operational stresses initiate cracks in weld material or base material especially if material is hardenable due to fast cooling to Martensite. Problem increased by welding heat being removed too quickly in large and cold materials, poor construction, poor design, welding patches/patch, and other weld deposits

CASE9, Title:- Fatigue failure of springs
Description:- Fatigue failure of springs, spring under compression, stretching, reverse bending or torsional stress \stresses. Typical components to fail include car suspension, clockwork drives, valve spring

CASE10, Title:- Contact corrosion, welding with more or less noble electrode
Description:- Contact Corrosion, Welding with more or less noble electrode than the bulk material. Welds of this type corrode at either the bulk material or the weld material, due to the electro-potential difference between two different materials

CASE11, Title:- Prematurely broken spring due to defects causing fatigue failure
Description:- Prematurely Broken Spring due to defects causing Fatigue failure of springs, spring under compression, stretching, reverse bending or torsional stress \ stresses. Typical component to fail include car suspension, clockwork drives, valve spring.

CASE12, Title:- Keyway failure due to high hardness of surface and high stress cycles
Description:- Keyway failure due to high hardness of surface and high stress cycles. Keyways have small radii. This can lead to stress concentrations and high Kt , Kf values. Also surface defects in that area can also lead to fatigue failure.

CASE13, Title:- Fatigue failure due to sharply edged formation
Description:- Fatigue failure due to sharply-edged formation (corner, notch, small fillet radius, crevice, holes, craters) due to high hardness of surface and high stress cycles, surface and sub-surface defects with small radii, lead to stress concentrations and high Kt , Kf values leading to cracks.

CASE14, Title:- Stress corrosion cracking in austenitic chromium nickel steels

Description:- Failure by cracking under combined action of corrosion and tensile stress, either external or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. In an Austenitic chromium nickel steels, S.C.C can occur in chlorine compounds.

CASE15, Title:- Corrosion mechanical wear at corner, bends, junctions in pipes
Description:- Corrosion mechanical wear at corner, bends junctions in pipes due to turbulent flow at corner, bends change in sections. Turbulence causes localised rupture failure and corrosion increased by dispersed solids particles in flow (water, gas).

CASE16, Title:- Tensile shock overload failure on a carbon steel aircraft towing cable
Description:- Tensile shock over load failure on a carbon steel (aircraft) towing cable. Shock loading increases at turns, stop, and starts, to increase stress past its tensile strength for material. Initial necking and unwinding of cable before failure

CASE17, Title:- Brittle cracks in steel due to low cycle fatigue from preexisting crack
Description:- Brittle cracking in high hardness (bearing steel) steel due to Low-cycle fatigue from preexisting crack, caused by poor processing, over heating, as seen by surface defects, corrosion, erosion,
surface remelting producing high surface hardness, transverse cracks due to quenching, poor electro-discharge machining EDM processing.

CASE18, Title:- Processing induced fatigue fracture in aluminum alloy component
Description:- Processing-Induced fatigue fracture in Aluminum alloy component. Poor multiple plating, chemical etching, anodising, , can produce pits, pitting corrosion in surface are initiation sites for fatigue fracture. surface is flat, shiny, reflective facets, Baking can reduce mechanical strength

CASE19, Title:- Subsurface defect leading to fatigue failure in critically loaded part
Description:- Subsurface defect leading to fatigue failure in critically loaded component
Subsurface defect such as inclusions, voids, pores , precipitate, crack, manganese and ferrous sulphides, phosphorus, silicon oxides, segregations, etc, leading to fatigue failure in critically loaded component

CASE20, Title:- Surface contact fatigue (pitting) failure of a gear
Description:- Contact Fatigue failure of a bull gear, due to continual overloading of gear and a poor quality non-uniform case hardening

CASE21, Title:- Overload failure in a sand cast aluminum base alloy

Description:- Overload failure in a sand cast Aluminum-base alloy, this can be seen by extensive cracking and evidence of substantial deformation in the region around stress concentrations such as holes, corners, keyways. Generally material (LM6) is in specification.

CASE22, Title:- General overload failure
Description:- Overload failure in a material, can be seen by extensive cracking and evidence of substantial deformation in the region around stress concentrations such as holes, corners keyways. Generally material is in specification and in good condition.

CASE23, Title:- Flow erosion in pipes
Description:- Turbulent fast velocity flow in pipes can cause erosion leading to leakage. This could be in a plastic, copper or an non-corroding material . Wear patterns show Wall thinning at areas of fast flow or turbulence (eddies), and deposit build up in areas of low flow with the reduction in mechanical properties. Welding bead protrusions on the pipe inside wall increase the problem.

CASE24, Title:- Stress corrosion cracking in 300 series stainless steel
Description:- Failure by cracking under combined action of
corrosion and tensile stress, either external stress or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. Austenitic stainless steel 300 series undergo SCC when subjected to chloride solutions. Nuts and bolts increase the SCC due to the cracks, crevices and threads

CASE25, Title:- Impact spalling in steel
Description:- Spalling is the cracking and flaking of particles out of a surface, caused by two surfaces (forge, rolling mill, hammering,) been together under a cyclic load in which the subsurface shear strength is inadequate to withstand the shear stress. The surface is generally harder than the core. Crack start, subsurface at inclusions where the contact stresses are maximised. Sliding action, (bearing or contact roller), may initiate crack at the surface, forming pits Linked to contact fatigue, pitting and high contact stresses.

CASE26, Title:- Cracking on the parting line of closed die forgings
Description:- Crack can occur at a parting line in a forging. These can grow during heat treatment. A large grain structure and high temperature scale can be seen around parting line, which is not normally seen in forged components. Associated with carbon and low alloy steel.

CASE27, Title:- Creep failure of a superheated tube by graphitization / spheroidization

Description:- Creep is a slow plastic deformation failure dependent on materials, time, with temperature, and service stresses, which can be small and static. This would be seen as a longitudinal rupture or deformation near a bend. Graphitization / spheroidization occurs in Carbon Molybdenum steels at temperatures above 420 C

CASE28, Title:- Corrosion fatigue failure
Description:- Corrosion Fatigue Failure is caused by a combination of fluctuating stress and an aggressive environment (ph changes & higher temperatures) which proportionally increases crack growth and reduces fatigue life. Increasing the corrosive environment reduces the fatigue initiation stress

CASE29, Title:- Ductile overload
Description:- Ductile overload occurs in tension, bending, and torsion. Where the component undergoes plastic extension, then necking at a weakness and triaxial stresses are set up to produce a central crack and 45 degree lips (shear planes) at the edges. a dimpled central fracture and plastic deformation are signs of a ductile failure.

CASE30, Title:- Liquid metal embrittlement of copper alloys (Brass) by liquid metals
Description:- Liquid-metal embrittlement is the brittle intergranular failure with little indication of crack branching or striation to indicate slow crack propagation, of a normally ductile metal when coated with a thin film of liquid metal and stressed. Mercury especially, and also Antimony, Cadmium, Lead, Tin, Lithium, Sodium, Bismuth, Gallium, Indium, Thallium embrittles Copper, which increases when alloyed with Aluminum, and zinc (Brass)

CASE31, Title:- Liquid metal embrittlement (LME) of steel by liquid metals
Description:- Liquid-metal embrittlement (LME) is a brittle intergranular failure with little crack branching or striation to indicate slow crack propagation, in a normally ductile metal when coated with a thin film of liquid metal and stressed. Crack growth is fast. Initiation occurs at solid-liquid metal interface. Steel is LMIE by Mercury, Gallium, Sodium, Indium, Lithium, Tin, Cadmium, Lead, Zinc, Antimony, Tellurium, Copper.

CASE32, Title:- Fracture of a cast component due to low strength & large grain sizes
Description:- A low strength material with a large grain size undertaking a high load. Cyclic loads lead to fatigue failure. Plastic deformation and orange peel are features of this failure.

CASE33, Title:- Hydrogen embrittlement failure of maraging steel bourdon tubes

Description:- Cracking by Hydrogen embrittlement in maraging steel bourdon tubes. Processing involved bending tubes after filling with low melting alloy, which is then melted out. Incomplete removal of alloy occurring would lead to dissimilar metal corrosion (pitting) in service, the cathodic half reaction being hydrogen evolution. Axial & circumferential (initiate from drill marks) crack possible.

CASE34, Title:- Sulphide stress corrosion cracking

Description:- Sulphide Stress (sour) Corrosion (brittle)Cracking occurs with oil & gas due to hydrogen sulphide gas, hydrogen sulphide, & water. More corrosive when moisture, oxygen and carbon dioxide are present. Seen as pitting corrosion & corrosion-erosion. Generally occurs in high strength materials with the application of external stresses. Increases at room temperature. Susceptible materials are stainless steel & Nickel alloys

CASE35, Title:- Torsional fatigue failure of shafts

Description:- Torsional Fatigue Failure of shafts can be seen by the star-formation on the fracture surface. Typically the initiation starts at keyways, holes, splines and changes in cross section. Multiple initiations from each stress raiser are not uncommon (splines). Cracks are at 45 to the shaft axis

CASE36, Title:- Excessive wear of a single sprocket or gear

Description:- Excessive wear of a single sprocket or gear, by other sprockets or gears may be due to poor manufacture, or hard surfaces/particles in other sprockets/gears, as the failed gear is softer than the others. The surface is likely to look scratched, then scuffed, and finally scored with increased wear.

CASE37, Title:- Adhesive wear of gears causing pits, welded particles & tooth failures

Description:- Adhesive wear of gears occurs on sliding surfaces when the contact pressure causes plastic deformation and adhesion. Surface glazing followed by galling then seizure and failure occurs. Galling is the adhesion of sliding surfaces which pull areas of material off one surface. So one surface has pits and the other has bumps. Broken teeth and total gear failure possible. Can be caused by other foreign objects

CASE38, Title:- Internal stress rupture in a gear tooth

Description:- When internal residual stresses build up to a point which exceeds the strength of the material, rupture will occur. The internal rupture of a gear is linked to the case core transition interface zone near the top face or the corner of the tooth. Separation of the case/core can remove the top of the tooth

CASE39, Title:- External stress rupture in a gear not in service

Description:- When the gear in not in service external stress rupture originates from a stress raiser and
residual stresses. This could be poor grinding, sharp notches, tooth undercutting. If residual stresses build up to a point which exceeds the strength of the material, rupture will occur at the stress raiser. The stress raiser is generally not the entire cause of the failure but provides the initiation point.

CASE40, Title:- Tooth bending impact and shear failure of gears
Description:- When a tooth is removed from the gear within a few cycles (one or two) with a uniform fracture with no striations, this is tooth-bending impact. Generally random failure due to shock loading and not just at root radius. Commonly in combination with "Tooth Shear" failures which are due to high stress & short time impacts with resultant failure by shear across the tooth to a convex shape.

CASE41, Title:- Tooth chipping of gears
Description:- An impact failure, though not considered to be tooth-to-tooth impact, but an external force, such as a foreign object (Bolt, a broken tooth from another gear). Random chips, lumps, taken out of the gear, with a general brittle nature. However mishandling causes most chips

CASE42, Title:- Case crushing failure of a carburized case hardened component
Description:- Case crushing will occur when a high load/stress is applied to a carburized case on a steel surface and this is linked to gear failures. May be seen as small surface cracks and subsurface defects. Depends on stress applied, radius of contact, thickness of carburized case and core hardness.

CASE43, Title:- Thermal fatigue in gears
Description:- Not necessarily correct, but its linked to frictional heating. Found mostly on rotating faces of gears, that are exerting a high thrust, but also on active profiles of gears. Thermal expansion (heating) and contraction (cooling) initiates a large number of radial cracks and progress to fatigue cracks into the bore of gear and along the roots of the teeth.

CASE44, Title:- General corrosion
Description:- General Corrosion, involves uniform attack, produces thinning of the material. Caused by incorrect material for the environment. Prevented by use of different corrosion-resistant material, a protective coating, or the use of cathodic protection.

CASE45, Title:- Galvanic corrosion

Description:- Occurs when dissimilar metals are in contact with each other in a conductive solution (electrolyte) Corrosion rate increases when metal are far apart in galvanic series and more aggressive environments. Also when anode (Corroded metal) is smaller than cathode.

CASE46, Title:- Crevice corrosion

Description:- Crevice Corrosion occurs at bolted & locknut joints, junctions, cracks, poor quality welds or under deposits between metal and or non-metals allowing concentrations of corrosive species, particularly chloride ions to be generated within a crevice or stagnant area.

CASE47, Title:- Pitting corrosion

Description:- Pitting Corrosion similar to crevice corrosion but localized around small pits or cavities on a metal surface due to differences in oxygen and ion concentrations at base of pit which becomes anodic, compared to the surrounding metal which atmospheric oxygen can diffuse. Found commonly in the presence of chloride ions.

CASE48, Title:- Intergranular corrosion

Description:- Intergranular Corrosion involves preferential dissolution of grain boundary phases or adjacent zones, due to the formation of an anode because of the precipitation of a second phase. Occurs in many materials, i.e. stainless steel, Aluminum and nickel alloys

CASE49, Title:- Dezincification and denickelification

Description:- Dezincification is a selective leaching process in brass, whereby zinc dissolves and a brittle low strength spongy porous copper deposit remains. In Copper-nickel alloys, nickel is leached out, (denickelification). Linked to exposure in fresh or sea water with boats, shipping, nuts, bolts, pipes, etc and heat exchangers. Can occur after exposure to fresh or sea water, brass develops copper-
coloured layers or plugs of material.

CASE50, Title:- Sulphide stress corrosion cracking in pipe lines

Description:- Brittle failure in a high-strength steel by cracking under the combined action of tensile stress and a corrosive environment of water and hydrogen sulphide, (H2S). Cathodic corrosion process. Sulphide Stress (sour) Corrosion (brittle)Cracking occurs with oil & gas due to hydrogen sulphide gas, hydrogen sulphide, & water. More corrosive when moisture, oxygen and carbon dioxide are present. Seen as pitting corrosion & corrosion-erosion. Generally occurs in high strength materials with the application of external stresses. Increases at room temperature. Susceptible materials are stainless steel & Nickel alloys

CASE51, Title:- Hydrogen pressure cracking in pipe lines

Description:- Brittle failure in a lower-strength line pipe steel (>550 MPa) by cracking along the rolling plane under the combined action of tensile stress and a corrosive environment of water and hydrogen sulphide, (H2S). Cathodic corrosion process, associated with non-metallic inclusions (manganese and calcium sulphides also bands of hard transformation products in low strength materials). Seen as blisters, straight and step cracking.

CASE52, Title:- Decarburisation of steel
Description:- Decarburisation occurs at high temperature with hydrogen or oxidizing atmosphere or chemical substance, which reacts with carbon in steel alloys to reduce the carbon from the surface layer causing loss of fatigue and tensile strength

CASE53, Title:- Micro biological corrosion
Description:- Bio-Fouling and Bacterial corrosion in marine, oil fields, aluminum jet fuel cells, and sewage pipe environments are caused by anaerobic & aerobic bacteria, fungus, and macro-organisms (barnacles, mussels, etc) change air, oxygen, and pH levels to acid, through reduction or oxidation of sulphur compounds and the suppression of cathodic reactions.

CASE54, Title:- Temper embrittlement (Ductile to brittle transition type fractures)
Description:- Low-alloy steel that are either cooled slowly through 600 to 350 C or prolonged exposure to that range could be subjected to intergranular failure accompanied by a large increase in ductile to brittle transition temperature. Mostly occur in body cantered cubic structures (non-austenitic steel)at low temperatures.

CASE55, Title:- Radiation embrittlements (Ductile to brittle transition type fractures)
Description:- Neutron embrittlement. Irradiation of Low-alloy steel could cause large increase in ductile to brittle transition temperature and be subjected to an intergranular failure. Mostly occur in body cantered cubic structures (non-austenitic steel) at low temperatures. X-ray, gamma, heavy-particle radiation or fission fragments in nuclear fuel also alter material properties

CASE56, Title:- Caustic cracking due to poor rivetted seams in a steel ships' boiler
Description:- Poor rivetted seams leave cracks & crevices for water to collect and evaporate thus concentrating the levels of sodium carbonate (sodium hydroxide). Possible white crystalline deposits seen indicate caustic alkali. Similar to stress corrosion cracking. Occurs in steels (iron & iron-chromium-nickel alloys)

CASE57, Title:- Brittle fracture of a rail arising from flame-cutting

Description:- Brittle fracture of a rail arising from flame-cutting of slots. Crack originate from corners and the hard martensitic structured surface layer caused by the rapid heating and cooling into the large cold rail mass.

CASE58, Title:- Fatigue fracture due to abrupt thread run-out
Description:- Fatigue fracture due to abrupt thread run-out occurs at localities where there are high bending stresses as in lifting swivelling shackles, and nut and thrust-race combinations. Fatigue cracks initiate at the root of the last thread and propagate in the direction of stress

CASE59, Title:- Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin
Description:- Fatigue cracks originated at overlay welded shaft on a ferry stabiliser fin (welded by Fleet fusion process with Inconel 625, 1mm thick on BS970 steel) & propagated inwards for 13% of stock before failure, under bending loading conditions in sea water, which due to corrosion reduced fatigue strength. EM/1538/90

CASE61, Title:- Brittle fracture due to strain age embrittlement in a mild steel hook
Description:- The hook conformed to B.S.482, & used in an overhead hoist in a foundry. Failure was initiated at pre-existing crack defect, due to poor manufacture. Then exposure to radiant heat from molten metal and being plastically strained would lead to strain-age embrittlement. Thus a ductile material would become brittle & notch sensitive. British engine boiler & electrical insurance technical report 1965, Vol.VI, pp81-87

CASE63, Title:- Hydrogen embrittlement
Description:- Hydrogen embrittlement cracking occurs in high strength steels (Quench + tempered, Precipitation hardened) at ambient (room) temperatures. Seen as brittle (quasi) cleavage intergranular or transgranular fractures with little plastic deformation. H2 cracking increases with strength from 690 MPa and with decreases in strain rate. Does not occur above 200 C

CASE64, Title:- Hydrogen induced blistering
Description:- Hydrogen induced blistering occurs in low strength alloys (steels) in corrosive & stress environments e.g. oil, petroleum, sour gas, propane pipelines where sour hydrogen sulphide hydrocarbon are present. Also in acid pickling and on steel cathodes for electrolysis plating. It requires inclusions (manganese sulphates), precipitates, or martensite bands to be present.

CASE65, Title:- Cracking from precipitation of internal hydrogen, (Fish-eyes)

Description:- Also called Fish-eyes (under bead cracking in welding). Occurs in steel forgings at temperatures below 200 C in the form of small elliptical bright cracks (flakes). If welding is involved then under bead crack can occur in heat affected zone (HAZ) that can occur hours or days later

CASE66, Title:- Hydrogen attack
Description:- Hydrogen attack, occurs at elevated temperatures, where the Hydrogen reacts with the substrate especially in petrochemical plants (oil, gas) at high pressure areas. Unaffected for days/months then a sudden loss of strength & ductility. Decarburisation of iron carbides to produce fissuring containing methane at grain boundaries. Effects copper and silver as well

CASE67, Title:- Hydrogen cracking from hydride formation (Titanium)
Description:- This occurs in Transition, rare earth, alkaline earth metals & also in Titanium, Tantalum, Zirconium, Uranium, Thorium & their alloys. It causes increased strength but losses in ductility and toughness. Welding & melting picks up Hydrogen for hydride particle formation on cooling to give platelets with preferred orientation to parent lattice but with volume change

CASE68, Title:- Impeller failure due to repair or built up welds with pores
Description:- A Cr Ni Mo steel impeller (propeller) suffered failure after 170 hrs service, @ 720 rpm, = to 7.3 x 10E6 stress reversals with cracks around impeller root areas Hardness was 284 HV (10kg). Surface was consistent with high cycle fatigue under conditions of bending stresses. The fatigue origin was a large sub-surface pore. It had been repaired/built up by welding containing pores. EM/1613/90
BROWSE GRAPHIC TOOLBOOK : seacat1 PAGE : c\cbrx13dk

CASE70, Title:- Delamination & longitudinal split in extruded aluminium alloy mast
Description:- BS 1474 6061 Aluminium alloy mast delaminated & split longitudinal due to poor extrusion, seen as extremely coarse grains due to slow cooling rate. Also dross, piping defects, & back-end defects lead to delaminations & areas of high friction - poor flow, produce oxide accumulation thus lead to poor welded joints, thus longitudinal splits
EM/1547/90

CASE73, Title:- Ductile flat face tensile fracture
Description:- Occurs in ductile materials by triaxial tensile stresses. fracture plane is normal to the largest tensile stress. Necking precedes fracture & ends by shear lips that extends to the free surface. Area ratio of flat face fracture to shear lip increases with section thickness. examination will reveal equiaxed dimples formed by microvoid coalescence.



CASE74, Title:- Ductile shear face tensile fracture
Description:- Occur in ductile materials under plane stress conditions in thin walled sections or near free surfaces with or without necking, and at 45 angles to surface in steel fracture surface are fine silky gray, and faintly visible Necking in threaded areas (bolt). examination reveals elongated dimples with their long axis in the direction of the shear force. Pointing in the opposite directions on the mating fracture surfaces.

CASE75, Title:- Fretting fatigue
Description:- Browse Graphic ToolBook : run Page : c:\data\html_fil\fretting.htm

CASE76, Title:- Buckling failure
Description:- If an eccentric point load is applied to a beam, post or column under a high magnitude compressive load, excessive deflection occurs. Generally in combination with bending and typically seen in supports and ladders.
Browse Graphic ToolBook : run Page : \html_fil\buckling.htm

CASE77, Title:- Brinnelling failure
Description:- When the static force or load between two curved surfaces in contact results in local permanent plastic yielding. Ball bearing race can become brinnelled leading to increased vibration, noise, and heating.
Browse Graphic ToolBook : run PAGE : \html_fil\brinnell.htm

CASE80, Title:- Gaseous corrosion in 300 series stainless steel
Description:- Gaseous corrosion in stainless steel is due to a nitrogen atmosphere (HCl, Cl2) and the presence of hot gases (e.g: combustion gases). A high percentage of nickel is necessary to guard against gaseous corrosion, e.g. 600 series nickel superalloy.

CASE81, Title:- Internal cracks in cast steel 9% Ni
Description:- Internal cracks that occur in Ni steel castings originate at austenitic grain boundaries that coincide with primary dendrite interfaces. The decrease of grain boundary cohesion arises from sulphur segregation. The addition of molybdenum is remarkably effective for preventing internal cracks.

CASE82, Title:- Electrostatic discharge attack on a thrust bearing
Description:- Electrostatic discharge attack is caused by stray electrical currents. Such currents may result from residual magnetism. The presence of corrosive material, such as

sulfides, contribute to failure by introducing unwanted deposits. Arcing damage also possible. Common in ship, boats, and liners propellor bearing using electrical cathodic corrosion protection.

CASE83, Title:- Impact failure induced by water hammer on a welded pipe
Description:- A welded pipe failed because of an impact induced by water hammer. This brittle failure is also the result of a combination of poor notch toughness and high stresses in the welded joint area.

Chapter 9 Question within the expert system

9.0 Introduction

Questions are designed to help in the identification of the failure mode. The failure modes are held as cases. Thus, questions are added to a case description to confirm various aspects of the case. Often these questions just repeat and verify the case description. Questions may also be used to rule out cases, or to confirm them.

The first role of the questions is to confirm characteristics of the case already mentioned in the case description. For example "Has grinding been undertaken?" "Has the component been electroplated?" These will lead the system to start confirming appropriate general areas of matching cases. These answers to these questions are generally of the "Yes or No" type.

The second purpose of the questions is to guide the operator into a dialogue that elicits more exact information. "What is your material?" "What are the environmental conditions?" These questions probe for information the operator may not have mentioned in the initial description and are generally of the list type. This sometimes requires additional explanation. However the amount of information within a question requires a balance between just enough for a non-expert and not too much information for an expert. Additionally if a question is too long then it becomes both unreadable and unmanageable in a programming sense. The first bit of information on a question is the question title. If the user does not understand the question title additional information can be browsed. For instance, if the question says, "Is your component a spring?" most people would know if their component were a spring or not but if the question was "Can you detect a fatigue crack?" most consultants would know how to examine a component and know what is considered a fatigue crack. But as this expert system is meant for a wide group of users with different levels of knowledge, most people would need some instructions before proceeding to answer the fatigue crack question. This could be in the form of diagrams or photographs in external ToolBook (*.tbk) or world wide web files (*.html), which are currently being developed for several different failure modes.

9.1 Questioning strategy

An effective questioning strategy involves: selecting the description, order, weighting, types (yes/no, list) and number of questions by which to ascertain the most important facts. Some information is well known and generally requires little analysis. Such questions are easy to answer and therefore should be the first to be answered, e.g. What process /component /material?; What temperature? Room, Elevated, High; What time to failure? Very short, Short, Long.

Most information in failure analysis is very difficult to quantify. Typical examples are stress levels at stress raisers, or pH levels for local concentrations of solution. These can be measured in a static state, but as most systems undergo dynamic interactions with their environments, these factors are difficult to measure. (See Table 9.1). In Table 9.1, the availability of information is compared against

the type of information for different failure influencing factors (Loading, Composition, and Environment). Thus an engineer is likely to know the static loads on a component but is very unlikely to know the level of local concentrations. Thus questions should relate to the information that is readily available because other information is likely to have considerable errors especially if users guess the values. Similarly, with either the composition or environment, the engineer is likely to know the nominal or general conditions, but is unlikely to be able to readily find out the local differences in composition or environment. Although the answers to for example, "What force? Steady or Cyclic." seem vague, inferences can be made, such as: a cyclic force suggests fatigue, whereas a steady force reduces the probability of fatigue. Note that a steady force only reduces the probability of fatigue, because cyclic stresses whether mechanical, thermal or vibrational could be undetected or unknown to the engineer. Information that is readily available is generally found by looking at an easily observed situation.

AVAILABILITY	SYSTEM CONDITION	LOADING	COMPOSITION	ENVIRONMENT
Information easily & simply available	General condition	Static loads	Nominal composition	Environmental pH levels
Readily available	Interactions to the system	Dynamic loads	Processing imhomogeneities	Chaotic fluid dynamics
Difficult to access	Local differences	Local stress concentrations	Local Compositional changes	Variations local pH variations
Information very difficult to assess	Complex combinations of different systems	Combinations of all the different influencing factors		

Table 9.1. The availability of information compared with the type of information for different failure influencing factors.

For example for the case of a truck parked on a bridge, it could be assumed that this was the total load on the bridge apart from the weight of the bridge. This is an easy situation to visualize and hence calculate the loadings on the bridge. However, a more detailed analysis would consider the wind and thermal loadings on the bridge as well as the truck. The main problem is that it is very difficult within the confines of the generic computerized expert systems presently being developed, to identify all the factors on the truck and bridge easily unless the expert systems has an extensive knowledge of wind effects etc., and an extensive list of questions.

It is at this point that is important to consider again who would use the system. An expert would require less general and more specific information, as the expert might have

already taken into considerations the wider interaction on the system. The non-expert might not consider the wider interaction and so would require more prompting. In programming terms, it is easier to design a tool for an expert as this would require less work. With a non-expert, the Expert systems would require more questions, and this complicates programming the logic, to the point where the Expert systems does not produce accurate prediction or diagnosis.

Case specific information is asked last. A case specific question relates to information that only affects one case within the case-base, e.g. Is there a liquid metal to solid metal interface (e.g. Hg and Cu alloy). This is directly related to liquid metal embrittlement.

9.2 Answering questions

The question stage presents a menu of questions to the consultant/student to elicit more information specific to the failure problem. From the description and questions in the search panel, a numerical similarity score is developed which is the result of comparing the search case and stored cases. Algorithms in the expert system shell give a zero to 100 percent score for a similarity match between search panel cases and stored cases, where 100 percent represents a perfect match. Each time a question is answered, the search is updated. The question list contains all of the questions associated with the five best-matching cases and serve to help differentiate these cases from one another. Each question appears only once (no duplication), and with the most promising questions listed first. The questions may be answered in any order, and it is not necessary to answer them all. The user simply supplies the information that is readily available.

Sometimes questions will be seen in the list that do not seem pertinent to the current case. These can be ignored as the matching algorithm can produce false hits in certain cases, particularly if the search description was vague or very short, or if the case-based system happens to be very small. There is no penalty associated with leaving a question unanswered.

If questions are not understood, the program provides a means to browse additional information about a question by double-clicking the mouse pointer on the question text. This produces either a scrolling text field to display a full explanation of the question or a graphic presentation about how to answer it. Also it is always possible to mark a question "Not Answered".

9.2.1 Question types used in development

Though the expert system shell, CBR Express supports four types of answers to questions: Yes or No, Numeric, Text, and List, as detailed in section 4.6.3, these have not all been used at this stage of the development. Mainly "Yes or No" and "List" types of answers were used. This was due in part to the complex and numerous terms used in failure analysis. These are described in section 8.5

The four Answer field responses are detailed as follows:

Yes or No questions are answered by means of a dialogue box containing buttons for Yes, No, and Not Answered. Alternately, a faster method is simply to highlight the answer using the arrow keys, then set the answer in one step using Y for yes, N for no, and T for not answered. This method bypasses the dialogue box for a faster throughput.

List answers pop up a dialogue box containing a scrolling field of legal answers. Simply click the mouse on the answer preferred, and click on the Answer button to confirm. This selects the answer and dismisses the box.

Numeric answers pop up a dialogue box for user input. This box accepts numeric values only, and enforces a maximum and minimum value limit on each question. Just type in the number and press the Enter key to dismiss the box. The numeric answer will appear in the scrolling answer field.

Text answers pop up a dialogue box containing an editable field. Unconstrained text may be typed in this field. The enter key is pressed when typing is complete to dismiss the box.

9.3 Evaluation of the questions

The process of developing the questions was very similar to that used in developing the actions as detailed in chapter 10. The questions were kept to a minimum, and this was done by combining two similar questions, through a process of evaluation. Questions must be useful! If a question does not help locate cases, it was discarded or combined with another. It was very easy to develop lots of questions for each case description but this is not very useful in a search. One way to recognize questions which are not useful is to observe which questions are avoided by the users, usually because they do not know how to answer, or just do not care. If the user repeatedly avoids answering a question, it should be considered for removal from the case-base.

9.4 Question details in the expert system

Each question in this section has either been or is in the expert system. Some questions have been removed, edited, or combined with another question, during an on-going process of evaluation. Reasons for their removal or editing are given, together with a full description of the intended purpose of the question

Each question has a match and mismatch weights, (See section 8.3) in which the values are set relating to the importance the author considered then to have in helping to determine the failure mode. If a question greatly affected the propensity for a given failure then the matching weight would be given a high value (e.g. over 27). However, if the question related to many different failure situations then the match weight would be given a nominal value (e.g. around 10 to 15).In between these two extremes an above nominal value (e.g. between 16 and 27) could be assigned. The setting of the matching and mismatching weights is complicated as different consultants would adopt different sets of values relating to their experience and background. Presently there is no ideal values associated with questions. However, further work in this area is paramount to increase the accuracy of the expert system. Methods to analysis different experts in the setting of the values need to be considered.

The values presently set in the examples above, are based on the author's understanding of failure analysis. For example if three questions asked for fundamental information and these three questions could confirm a failure mechanism then it is suitable that each question was given a high value (over 27) because the combinations of these values (81) would be sufficient for the expert system to confirm a matching case, and thus diagnose a failure mechanism. However, in the expert system, only very few questions have such a high score associated with them. If an error in inputting data associated with these few questions occurs, the errors should become apparent. In the design of the expert system, well known and readily available information was given a high value and less known information was given a lower value. This had the effect that general questions such as "what in the primary material" or "What is the main manufacture method" are given a high value (17 to 27), but are generally only answered once. This would quickly sort relevant cases and further questions because these general questions are fundamental to the propensity of failure. Other general failures which do not have such a fundamental effect on failure, and are asking for less known or difficult to assess information are given a nominal value (10 to 16), as it is the accumulation of answers to these questions that diagnoses failure mechanisms. Some questions are highly failure mechanism specific and are thus very highly valued (over 27) because answering the question would indicate the acceptance or rejection of that specific case.

9.5 Question listing and explanatory text

1 TITLE is the material soft or in the annealed state
ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :10 MISMATCH : 2

This question has been removed from the expert system and substituted with questions 42 and 43 which ask about the brittle or ductile behaviour seen in the failure and in the material. This is much more generic and covers many more manufacturing treatments and components. Combining questions and thus reducing the number of overall questions decreases the complexity and increases the speed of the expert system.

2 TITLE Is the material under any stress.
ANSWERS TYPE :LIST :High, Low, No Load
WEIGHT MATCH :11 MISMATCH : 2

During evaluation, this question was replaced with a more relevant question with the associated explanatory text, as follows

2 TITLE What level is the stress, (High, Low, or No load)
TEXT If the component is under a stress level which you would consider greatly contributed to its failure then select High.

Stress intensity factor (KIscc), is the threshold stress intensity for stress corrosion cracking when conditions meet plane strain requirements. It is important to know this as if the stress is above the threshold stress intensity factor (KIscc), then stress corrosion cracking has to be taken into consideration, as well as corrosion fatigue. However finding both the stress intensity in a component and relating it to a materials KISCC is difficult. Hence, if it is believed that there is some loading or it is known that the stress intensity factor is above KISCC then select low stress load.

If you believe that the component is under no stress loading at all or you wish to consider failure mechanisms which are associated with low or no stress situations select No load

ANSWERS TYPE : LIST
High
Low
No load
WEIGHT MATCH : 28 MISMATCH : 2

3 TITLE Is the component at or above 0.6 of melting temperature in service

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :11 MISMATCH : 2

During evaluation this question has been replaced with a LIST question (question 55) which covers this and others related to service temperatures such as question 39.

4 TITLE What is your primary material

TEXT A primary material is any material in your component which is in the majority. If you are not sure then choose a secondary material. For example you could choose austenitic stainless steel as your primary and choose carbon steel as your secondary material. In fact by choosing both types of steel you cover all aspects because although different materials will undergo different modes of failure, and it is important to specify the material grouping, a number of failures will occur in many types of material. That is why the groups have been kept to a minimum, but from the rest of your questions the computer might choose a failure mode which is not specific to your material or link it to another material. In this case see if this relates to your component and or change the material specification because the computer or yourself might have missed or overlooked something in your specification of the material or failure situation. If you are having trouble please leave this question not answered.

ANSWERS TYPE :LIST :

Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)

Carbon Steels, (Body centred cubic, BCC)

Copper alloys (Brass (Zn) (Bronze, (Al,Sn,Si,ZnSi,Be,Ni,NiZn)

Aluminum alloys

Gold alloy

Titanium, Tantalum, Zirconium, Transition & rare earth metals

Overlay welded steel for corrosion and wear resistance

WEIGHT MATCH :27 MISMATCH : 3

This question has had the answer LIST updated to include overlay welded steel and to revise the description of Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC) and Copper alloys (e.g. 70% Copper , 30% Zinc, Cartridge Brass or Aluminum).

5 TITLE Has grinding been under taken

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question has been taken out of the expert system and substituted with a generic question on different manufacturing techniques.

6 TITLE Has the component been electroplated,

TEXT Cadmium plating poorly done can lead to hydrogen embrittlement. ("Standard recommended practice for safeguarding against embrittlement of Hot-dip galvanized structural steel products and procedure for detecting embrittlement," A 143, Annual Book of ASTM standards, Vol. 01.06, ASTM, Philadelphia, 1984, p 39-42) Also cadmium is very poisonous especially if heated, ie through welding or heat treatment

ANSWERS TYPE :LIST :

Hard chromium plating

Chemical etch and anodising

No electroplating

Cadmium plated

WEIGHT MATCH :15 MISMATCH : 2

This question could have been incorporated into more generic manufacturing questions. However, a component could be manufactured by machining for example, and yet also be electroplated. This match weighting is higher than average due to the importance of electroplating in failure mechanisms.

7 TITLE Is the component under stress

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

During evaluation this question was substituted by combining it with the old version of question 2 and 7 to produce a more generic LIST type question 2 on stress level.

8 TITLE Can you detect a fatigue crack

TEXT The surface of a fatigue failure consists of two areas. One is smooth, discoloured and has rippled markings like a mussel shell indicating the gradual growth of the crack from one or more centres, while the remainder of the surface has either a crystalline or a fibrous appearance which indicates the final tearing, which occurs when the area can no longer sustain the load.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question has been taken out of the present expert system due to its duplication with other questions related to fatigue. Question 34 has taken over as the main fatigue question.

9 TITLE Is there a source of hydrogen in the components environment

TEXT This could be atomic hydrogen, Hydrogen in water, or hydrocarbon liquids and gases. Hydrogen has a major effect on the strength of steel due to embrittlement and blistering.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :17 MISMATCH : 2

This question is very case specific, in that it relates to hydrogen embrittlement and cracking failure problems. Thus the answer to this case could either accept or reject cases related to hydrogen failure problems. With this in mind the match weighting value is higher than average and set at 17.

10 TITLE Is there an initial defect
ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :10 MISMATCH : 2

This question has been replaced during evaluation with an updated question 24, because this question was repeating question 24 and other associated questions, e.g. sharp corners, keyways, and other details with sharp changes in section.

11 TITLE Is there any damage near to the possible fracture sites
TEXT Damage near fracture sites could be the stress concentrations or initiation site for failure. The damage could include mechanical, environmental (corrosion, etc.) and welding or other processing damage effects. If a fracture has already occurred then this could mean that a ductile failure could produce shear lips at 45° to the applied stress.
ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :10 MISMATCH : 2

12 TITLE Are there any cracks perpendicular to the tensile stress
TEXT Perpendicular tensile stress has the effect of opening up cracks and so it is related to all failures which might have complex stress systems or any possible cracks.
ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :10 MISMATCH : 2

13 TITLE What are the primary environmental conditions
TEXT The environmental conditions relate to all concentrations of different vapours and liquids. If there is any doubt then suspect that there are environmental problems
ANSWERS TYPE :LIST :
NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Moist ammonia, mercurous nitrate (see ASTM B-154), and amines
FeCl3 Solutions, Acetic acid-salt solutions
Caustic soda solutions
Lead acetate solution
NaCl-K2CrO4 Solutions Rural and coastal atmospheres
Rural and coastal atmospheres
Fused Caustic soda
Hydrofluoric acid, Hydrofluosilicic acid

NaOH and H2S solutions NaOH-Na2SiO2,NaOH-H2S
Calcium, Ammonium, & Sodium Nitrite solutions, Mixed acids
H2SO4-HNO3
WEIGHT MATCH :10 MISMATCH : 2

This question is still at the evaluation stage because there are many different environments. Each environment can have a different effect on the propensity for many different failures. Many failure mechanisms still need to be examined as to which environments are the most active in their effect on the propensity for different failures. A reduction in the number of environments would be ideal, yet each of the different environments detailed above increases the propensity of a given failure. For example, Gold Alloy is affected by FeCl3, and Acetic acid-Salt Solutions which can lead to stress corrosion cracking. Although this might be obscure, if the expert system is to be generic then the expert system has to cover all these obscure failure modes. If these obscure failure modes are ignored the expert system would only cover common failure mechanisms. The environments which affect the majority of failure mechanisms are NaCl-H_2O_2, NaCl Solutions, Seawater, Air, Water, Water Vapour.

14 TITLE Are there any other possible solutions in the environment
TEXT The environmental conditions relate to all concentrations of different vapours and liquids. If there is any doubt the suspect that there is environmental problems. This question is intended to detail any other environmental conditions for the LIST
ANSWERS TYPE :LIST :
NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Moist ammonia, mercurous nitrate (see ASTM B-154), and amines
FeCl3 Solutions, Acetic acid-salt solutions
Caustic soda solutions
Lead acetate solution
NaCl-K2CrO4 Solutions Rural and coastal atmospheres
Rural and coastal atmospheres
Fused Caustic soda
Hydrofluoric acid, Hydrofluosilicic acid
NaOH and H2S solutions NaOH-Na2SiO2,NaOH-H2S
Calcium, Ammonium, & Sodium Nitrite solutions, Mixed acids H2SO4-HNO3
WEIGHT MATCH : 10 MISMATCH : 2

This is a similar question to question 13. However, an environment might have many different interactions. These could be either act together or due to some form of sequence of environment events. If the user selects the same environment in both questions than this is a checking mechanism to make sure that the user has selected the environment that they wished.

15 TITLE Would you consider the environment was corrosive in any way

TEXT The corrosive environment could be atmospheric, vapour, liquid, or solid

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :30 MISMATCH : 8

This question relates to all corrosion case specific failure cases. The description is vague because it is very difficult to access what degree of corrosion is a problem. This will vary for different failure mechanisms, but any corrosion observed will very likely have an impact on the propensity of corrosion failure modes.

16 TITLE Is the component under any stress whether steady or fluctuating

TEXT If the stress is fluctuating or cyclic then failure mechanisms related to fatigue are probable. In the majority of cases the stress is fluctuating, although this can be very small, it can still be sufficient to induce fatigue crack growth.

ANSWERS TYPE :LIST :

Steady,

Fluctuating

WEIGHT MATCH :17 MISMATCH : 10

This question relates to either fatigue or static overload problems, in that fluctuating or steady stress affects different failure mechanisms. This question is mildly case specific, therefore a higher than average matching weighting of 17 is used. However the answer is not that accurate and so the matching weighting is not as high as the corrosion question (question 15). The lack of accuracy relates to the inaccuracy in prediction of the actual stress, as these could be interactions of mechanical (loading, vibrations), and physical (sound, heat) stresses.

17 TITLE Are two metals either in close proximity to each other or touching

TEXT This question relates to the failure modes of corrosion, mainly galvanic corrosion and fretting failure problems.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :19 MISMATCH : 2

This question relates to the failure modes of corrosion, mainly galvanic corrosion and fretting failure problems. Being mildly cases specific, the weighting is higher than average. This is related to the main corrosion question (question 15) with its associated vague questioning.

18 TITLE Are two different metals touching each other

TEXT This question relates to corrosion, wear and fretting failure. Also it could be remotely related to overload or fatigue type failures as the load could be transferred via a connection. However although this question is loosely related to fatigue, it is more strongly related to corrosion, and mildly related to fretting being a less common failure mode.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :15 MISMATCH : 7

This question is similar to that of question 17 in that it relates to corrosion, wear and fretting failure. Also it could relate to overload or fatigue type failures as the load could be transferred via a connection. However this shows the problems of assigning questions to cases, in that just about any interaction can be associated with any failure mode although at times some failure mechanisms might be very remotely associated. The process used in this expert system is to make a judgement on the most likely failure mode and associated questions. So although this question is loosely related to fatigue, it is more strongly related to corrosion, and mildly related to fretting being a less common failure mode. Other questions will have a bias to other failure modes, for example fatigue is associated with questions 21, 26 and34.

19 TITLE Are a non-metal and a metal in contact with each other

TEXT This question is related to crevice corrosion as a crevice could be formed between a metal and non-metal, such as a plastic washer and a bolt. However it is less related to galvanic corrosion as galvanic corrosion required metals

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :17 MISMATCH : 3

This question is similar to questions 17 and 18. However it is less related to galvanic corrosion than questions 17 and 18. Crevice corrosion is still related as a crevice could be formed between a metal and non-metal.

20 TITLE Is the process of welding involved in your component

ANSWERS TYPE : YES_OR_NO

WEIGHT MATCH :23 MISMATCH : 1

This question has been combined to the generic manufacturing techniques question (questions 52, 56, and 57) to reduce complexity and question numbers. This was done after initial evaluation, and thus is not used in the present expert system.

21 TITLE Are there any sharp corners or sharp radii

TEXT Such as keyways, abrupt changes in cross sectional area, grooves, channels, cavities

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :16 MISMATCH : 1

This question relates to fatigue and other loading failures, which are all related to stress concentration at sharp corners and radii. Due to the common nature of fatigue and the importance of stress concentrations to the initiation of fatigue cracks, this question has an above average match weighting of 16.

22 TITLE Is your component a spring

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :50 MISMATCH : 0

This question is very case specific to spring failures of which there are few mechanisms. Thus the match weighting is very high at 50. To cut down the number of questions and complexity, during the evaluation, this question was combined with other questions to produce a generic component question (questions 53 and 54).

23 TITLE If welding electrodes are used, have they been damaged

TEXT If the surface of an electrode is damaged then the additives in the electrode coating could have been broken off. The additives give the weld its properties especially corrosion resistance as in stainless steel where Nickel and chromium are in powder form in the electrode coating.

This question is case specific to welding stainless steel and corrosion failures. However, it does not indicate the failure mode, but rather supports a decision as to the possibility of a failure mode. Also, in asking if the surface is damaged, the user will have to ask the welder or inspect similar welding rods. This is fraught with acquisition difficulties from the welders' memory and trying to inspect welding rods and making assumptions on the quality of used welding rods. Ideally, composition analysis of the welds would be done, but this can take time and cost money.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :11 MISMATCH : 2

24 TITLE Before failure was the surface in good condition, free from any initial defects

TEXT Is the surface in good condition, free from any defects, this means any pits, welding splatter, corrosion, knocks or worn areas. This relates to many different failure modes, including fatigue, spalling, corrosion, etc.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :17 MISMATCH : 2

This question is related to many different failure modes, including fatigue, spalling, corrosion, etc., yet it is an important consideration on the propensity for failure. Thus the match weighting was above average at 17. During evaluation the actual question description was made clearer by including the fact that it concerns 'initial defects before failure'. The previous description was " Is the surface in good condition, free from any defects".

25 TITLE Has the component failed earlier than expected

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question was removed from the expert system during the evaluation stage, because all the cases within the expert system are likely to have failed earlier than expected. Initially the idea was to include cases in which good practice meant it survived an exceptionally long service life. From these good cases the expert system an be used as a design tool. However, all components will fail given time and the experts' are actually concerned in failure. Thus the approach is more towards post failure investigations, rather than a design tools although it is still possible to use the expert system as a design tool.

26 TITLE Does your component have a keyway
TEXT A keyway in a bore or drive shaft creates a higher stress-concentration than the actual stress if no keyway was included. A keyway is expected to withstand a very high load that is either continuous or cyclic. The applied load to the side of the keyway is directly proportional to the gear or spindle radius, which is proportional to the radius of the keyway. Fatigue failure is very common at this point, especially if the radius is small and the load is high.

ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :19 MISMATCH : 2

This question is case specific and relates to the initiation of a fatigue crack at a keyway. The match weighting is higher than average, but not excessively high due to the fact that many components have keyways and this does not always mean that the keyway will always indicate a failure.

27 TITLE Has the component had a surface hardening treatment.
TEXT This includes Quenching, Carburising, Carbonitriding, Nitriding, and Nitro carburising, for ferrous materials and Precipitation age hardening, and Anodising for Aluminium alloys.

Anodising for Aluminium alloy describes a process whereby a coating is produced on the metallic surface by converting it to an oxide.
Carburizing results in a hard surface layer in ferrous materials which involves heating the material to the austenitic state in a carbon rich atmosphere so that carbon diffuses into the surface layers, then quenching converts this to martensite.
Nitriding involves diffusing nitrogen into the surface layers of ferrous alloys and thus hard nitrides are produced, hence a hard surface layer.
Quenching is a method of rapid cooling that can produce martensite in ferrous alloys. Martensite is the structure produced when the cooling rates from the austenitic state is too rapid to allow carbon atoms to diffuse out of the face centred cubic austenite and produce the body centred cubic ferrite. This results in a highly strained hard structure.

Ref:- Bolton, W. "Newnes engineering materials pocket book" Publ. Heinemann Newnes, 1989, ISBN-0-434-90113

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :12 MISMATCH : 2

This question was considered for combining with a more generic manufacturing technique question. However, many components could have had a hardening treatment and had some other form of processing. Thus it was kept as an individual question with an average weighting.

28 TITLE Does a gas flow around or through your component

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question has had the question description up dated from the following, "Is your component a pipe that has either a gas or liquid flow". The reason was to make it more generic to cover all different components. However it does pose the problem that the user could get confused and answer yes if the gas was air, and thus the weighting is only average, i.e. 10. Initially, the question was used to confirm erosion failures. However as the expert system developed it has been used more often to confirm that some failure mechanisms are not possible. For example, if a gas flows past the component, then it is unlikely to fail by microbiological corrosion as this is more likely to occur in water.

29 TITLE Has Electric discharge machining been used at the failure site

TEXT Poor Electric discharge machining processing can cause surface melting problems which lead to a thick and very hard (1100HV in steel) surface. This can cause cracking and premature failure.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question has been combined with the different manufacturing techniques to reduce complexity and increase speed. It is noted that this question is very case specific to failure problems associated with electrode machining, and thus it might mean that the question has to be re-instated if it cannot be successfully searched and found.

30 TITLE If the fracture surface is examined are there any subsurface defects

TEXT If the fracture surface is examined are there any subsurface defects. Subsurface defects could include the following:-(1) Constituents harder than the background or matrix which stand out in relief, e.g. phosphides in cast iron. (2) Blowholes and spongy places, which should be confirmed by focussing with a microscope on the side or bottom of the cavity. (3) Non-metallic inclusions: [a] Manganese sulphide (dove grey masses), round in castings, elongated in forgings; [b] iron sulphide (brownish yellow), in films around grain boundaries;

[c] slag, Mn-silicate has greenish tinge, iron-silicate is black, Al_2O_3 occurs as hard rounded particles; [d] copper oxide (blue); [e] graphite in cast iron (grey).This question is related to many different failure modes especially fatigue or other fracture modes which can initiate from these defects.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :37 MISMATCH : 2

31 TITLE Is your component a gear

TEXT This includes spur, spline, helical, herringbone, cross-axes helical, worm, internal, rack, bevel, gears. It is important so the inference engine can pick all gear problems. Typical failures are broken gear teeth via overload, fatigue, wear, fretting fatigue, and on long axis gears, torsional overload and torsional fatigue.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :45 MISMATCH : 0

This question has been excluded from the expert system and combined into a general component question (questions 52, 56, and 57).

32 TITLE If your component is a gear or shaft, does it have oil holes

TEXT Oil holes are intended to lubricate the rotating surfaces. Each hole may be a stress raiser that could be the source of a fatigue crack.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question is case specific relating to fatigue crack initiation from an oil hole.

33 TITLE Is there extensive plastic deformation around the fracture site

TEXT If there is extensive plastic deformation around the fracture site then this could mean that the component has failed by overload. Overload failure occurs when the stress over a cross sectional area exceeds what the material can withstand, i.e. above its tensile strength. Fatigue failures, reduce the cross sectional area (CSA) by the propagation of cracks from a defect, stress concentration, or corrosion site. For a given load, when the CSA, reaches a critical limit the component fails by over load. This is still called a fatigue failure. So an over load failure does not have a fracture surface like a fatigue surface. Additionally, fatigue failures generally produce little plastic deformation around a fracture site. However a ductile type failure always produces plastic deformation around the fracture site and thus this question is related to ductile failures rather than brittle and fatigue failures.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

34 TITLE Does the surface look like a fatigue failure

TEXT If you suspect that the surface is like a fatigue fracture surface, even if you are not wholly sure, then say yes. The surface of a fatigue failure, consists of two areas. One is smooth, discoloured and has rippled markings like a mussel shell indicating the gradual growth of the crack from one or more centres; while the remainder of the surface has either a crystalline or a fibrous appearance which indicates the final tearing, which occurs when the area can no longer sustain the load.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :20 MISMATCH : 2

35 TITLE Has a process of casting been used

TEXT Casting can have many effects on the properties of a material and these can lead to specific types of failures. If the material is worked again after casting such as by forging then the properties can be improved, but poor heat treatment and welding can reduce the material properties, such as elongation to failure.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question has been excluded from the expert system during evaluation and combined with a general manufacturing techniques question (questions, 53 and 54)

36 TITLE Is your component a pipe

TEXT Pipes can have distinctive failure modes, but are generally due to an initial defect, which can result from mechanical damage, fatigue cracks and material defects. Other failures occur from gross overload (secondary stress, internal combustion, or sabotage). A typical initial defect is most likely to be caused by a welding problem (lack of fusion, porosity, inclusions, lack of alignment, repairing, lack of penetration, etc.). Other different types of defects can be associated with environmental damage (Corrosion internal and external, Hydrogen- stress cracking, external stress-corrosion cracking, internal sulphide-stress cracking, hydrogen blistering), fatigue, and other miscellaneous causes (erosion, etc.)

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :15 MISMATCH : 2

This question has been excluded from the expert system during the evaluation and combined with a generic component question (questions 52, 56, and 57).

37 TITLE Does a liquid flow past, through, around, or next to your component

TEXT Fast flowing liquids, especially turbulent flows, can cause a great deal of erosion especially in boilers and pipework. This could happen inside a pipe, on the hull/propeller of a boat. In slow flows especially at high temperature, depositions can build up. In high temperatures the deposits are inorganic materials precipitated out of the liquid. High concentrations of solutes will increase the problem e.g. hard water areas. Organic material is a

problem at temperatures below 50 C. At low temperature, there is the problem of freezing to cause rupture failures and brittleness in materials which have a high brittle to ductile transition temperature. A liquid could also be a lubrication oil, as found in a gear-box. Gear box oil can be a problem if not changed at regular intervals, i.e. every 6-12 months, because small metal particles can be held in suspension within the oil. These particles can cause problems associated with wear, frictional heating, fatigue, and rupture.

ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :12 MISMATCH : 2

38 TITLE Has your component undergone a forging process
TEXT Forging can improve the properties, welds up small cracks and blow holes, refines the grain structure, eliminates oriented cast structure, and promotes uniformity of material by diffusion of alloy constituents and the breaking up of brittle films of hard constituents or impurities, e.g. cementite in steel. This all helps in ensuring quality and reliability, if the processing was correct. Sometimes the initial material casting may be poor; this can lead to cracking in the material. This is generally shown up just after or during forging. Another major problem, is in poor alignment of the two forging heads. This can fold material over the parting line and can occur also when trimming. The crack although small, and generally only show up after heat treatment, can be the initiation sites for failure, such as by fatigue, and stress corrosion cracking.

ANSWERS TYPE :YES_OR_NO
WEIGHT MATCH :13 MISMATCH : 2
This question has been excluded from the expert system during evaluation and combined with a general manufacturing techniques question (questions 53 and 54)

39 TITLE Has the high temperature limit been exceeded
TEXT The high temperature limit of material, is a temperature above which creep has to be considered as an important factor in design. Examples of these temperatures are detailed below in °C:-

Magnesium alloys	75,	Aluminium alloys	100,
Coppers	120,	Brasses	150-200,
Aluminium bronzes	250-400,	Phosphor bronzes	150,
Cupro-nickels	200,	Nickel silvers	150-200,
Titanium	250,	Titanium alpha alloy	250-350,
Cast irons	350,	Titanium alpha-beta	350-400,
Titanium beta alloy,	300,	Carbon steels	450,

Cr-Mo Steels	550,	18% Cr, 10% Ni, Steel	600,
25% Cr, 20% Ni, Steel,	750,	Ni-Cr alloys	800,

Ref. Bolton, William, "Hewnes Engineering Materials Pocket Book"1990, ISBN 0-434-90113
More information can be found in the latest edition of "Creep of Engineering Materials" by Iain Finnie and William R. Heller, Published by McGraw-Hill Book company.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question has been excluded from the expert system during the evaluation and combined with other questions (question 3) related to a general service temperatures (question 55)

40 TITLE Is the stress above the threshold stress intensity factor for SCC

TEXT Is the stress above the threshold stress intensity factor for stress corrosion cracking? Stress intensity factor (KISCC), is the threshold stress intensity for stress corrosion cracking when conditions meet plane strain requirements. It is important to know this as if the stress is above that corresponding to the threshold stress intensity factor (KISCC), then stress corrosion cracking has to be taken into consideration, as well as corrosion fatigue. However finding both the stress intensity in a component and relating it to a materials KIscc is difficult. Hence, if it is believed that there is some loading or it is known that the stress intensity factor is above KISCC then select “Yes”.

If you believe that the component is under no stress loading at all or you wish to consider failure mechanisms which are associated with low or no stress situations select “No”.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :10 MISMATCH : 2

This question relates to stress corrosion cracking. However it is very difficult to know the stress level and whether this is above the threshold stress intensity factor for stress corrosion cracking. Thus the weighting value is only an average value of 10.

41 TITLE Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)

TEXT At the interface between a liquid metal and a solid metal a problem of liquid metal embrittlement can occur which is a brittle intergranular failure with little indication of crack branching or striation to indicate slow crack propagation of a normally ductile metal when coated with a thin film of liquid metal and stressed. For liquid metal embrittlement to occur it requires the surface of the crack to be covered by a thin film of liquid-metal. If this is not so then it is likely that corrosion and or hydrogen embrittlement has occurred.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :25 MISMATCH : 2

This question is case specific and thus has a high match weighting of 25.

42 TITLE Has the failure occurred by a brittle or a ductile fracture
TEST This question relates to many different failure modes where this can be an important diagnostic feature. A brittle fracture is where very little or ideally no plastic deformation has occurred. The brittle fracture surface is generally shiny and where broken parts can be fitted together. However do not try to fit fracture surface together until a full photographic and compositional examination is undertaken as fitting together (or cleaning) can damage surface evidence useful to investigations.
A ductile fracture is where plastic deformation has occurred and this could be associated with a change in cross sectional area, necking, with a dull surface consisting of ductile dimple.
ANSWERS TYPE :LIST :
Brittle
Ductile
WEIGHT MATCH :17 MISMATCH : 2
This question relates to many different failure modes where this can be an important diagnostic feature. Thus the match weighting is above average being 17. However as this question is asking for a description which is subjective to each person's option of what is ductile and what is brittle, the actual match weighting is not as high as some for other case specific questions.

43 TITLE Would you consider your material to be either brittle or ductile
TEXT In this question it should be noted that the temperature, loading conditions, rate of deformation, cross sectional area, will affect the way a material behaves, especially if your material has a body centred cubic structure.
ANSWERS TYPE : LIST : Brittle Ductile
WEIGHT MATCH :10 MISMATCH : 2
This question is related to question 42. However this question is less subjective as to what is a ductile and brittle fracture, but more related to the general inaccuracies involved in assessing the ductile and brittle nature of the material. This could be very difficult and so the match weighting is only 10. This question in combination with question 42 gives an over all weighting of 27. This is especially useful when a normally ductile material has become brittle or vice versa.

44 TITLE What is your secondary material
TEXT A secondary material could be either one of two materials joined together or if you are not sure of your material then your second choice. Different materials will undergo different modes of failure, so it is important to specify the material grouping. Although a number of failures occur in many types of material, which is why the groups have been kept to a minimum, from the rest of your answers the computer might choose a failure mode which is

not specific to your material or link it to another material. In this case see if this relates to your component and or change the material specification because the computer or yourself might have missed or overlooked something in your specification of the material or failure situation. If you are having trouble please leave this question not answered.

ANSWERS TYPE :LIST :

Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Carbon Steels, (Body centred cubic, BCC)
Copper alloys
Aluminium Alloys
Gold alloy
Titanium alloys

WEIGHT MATCH :27 MISMATCH : 3

This question is similar to question 4 (What is your primary material), although the answer LIST is shorter. In selecting a secondary material the user is either considering a connecting part or re-emphasizing the primary material choice. As the material choice has considerable influence on certain failure mechanisms, the weighting is high for this question at 27.

45 TITLE If your component is a gear or shaft, does it have splines

TEXT Splines can extend along either a shaft or a bored hole in a shaft. The splines are intended to transmit a torsional load. Each spline may be a stress raiser that could be the source of a fatigue crack, especially if the root radius is small or damaged through poor machining. A typical failure mode could be via torsional fatigue, in which case the fatigue crack propagates at 45° to the shaft/ gear axis to produce a star-shaped pattern on the fracture surface. Failures are more common in shafts as the shaft is under a greater load than its mating bore.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :25 MISMATCH : 2

As the question description states it is very case specific to torsional fatigue failure of splined shafts and gears and therefore has a high match weighting of 25.

46 TITLE Is your component a shaft

TEXT Shafts can fail by fatigue (rotational, bending, crack at 90° to axis) (torsional fatigue cracks at 45° to shaft axis) gross overload (brittle, no deformation cracks propagate across shortest route) (ductile, gross deformation, necking, cup & cone failure)

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :20 MISMATCH : 2

This question has been excluded from the expert system and combined with a generic question on different components (questions 52, 56, and 57).

47 TITLE Has the failure occurred before the part went in to service

TEXT If a part or component has failed before it has entered service then it is very likely that there is a problem in the material and/or manufacturing method involved.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :18 MISMATCH : 0

This is mildly case specific, in that it relates to manufacturing and material failures. However, with this question there are many variables and thus the matching weighting is only above average at 18.

48 TITLE Does the affected area have less strength than the parent material

TEXT There are many reasons for a loss of strength, Some of these include, selective leaching, over aging, and normalising. (1)Some materials, especially alloys, selectively leach out one of the alloying elements, as in brass, zinc is leached out (dezincification), and in grey cast iron, the iron matrix can be leached out leaving the insoluble graphite behind (graphite corrosion or graphitization). Also the selective leaching of aluminum from copper alloy and of cobalt from a cobalt-tungsten-chromium alloy has been encountered. Selective leaching leaves the material porous and brittle with a loss in strength compared to the original material. (2) Another reason is over aging in precipitation harden materials, such as aluminium copper and aluminium magnesium alloys. (3) Or normalising in for example steel. Over aging or normalising could be due to fault heat treatment, or repair welds. Many Aluminium alloys specifically state that repair weld should not be undertaken, typically these include highly stress components like drive differentials in cars. In any welding or heating process will reverse previous strengthening heat treatments. Over aging can occur in old alloy structures, for example aircraft. Or structures which have high operational temperatures in which case creep and creep fatigue may be considered as failure modes.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :12 MISMATCH : 2

This question is related to several failure mechanisms and is very difficult to assess. Thus although very important in assessing failure modes, it is only given a weighting of 12.

49 TITLE Is there a covering of bacteria, fungus, or macro-organisms

TEXT Bio-Fouling and Bacterial corrosion in marine, oilfields, aluminum jet fuel cells, and sewage pipe environments are caused by anaerobic & aerobic bacteria, fungus, and macro-organisms (barnacles, mussels, etc.). These affect oxygen concentrations and lower ph. level (more acid), through reduction or oxidation of sulphur compounds. Cathodic reactions are also suppressed.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH :30 MISMATCH : 2

This is very case specific relating to microbiological corrosion problems. Thus the match weighting is high at 30.

50 TITLE Did the failure occur when the component was at High, or Room temperature and below

ANSWERS TYPE : LIST :

High temperature,

Room temperature and below

WEIGHT MATCH :10 MISMATCH : 2

This question has been excluded and combined with question 3 and 39 to produce a general question on service temperatures (question 55).

51 TITLE Has the component been neutron irradiated (nuclear reactors, etc.)

TEXT This question is highly case specific in that it is associated with radiation embrittlement. Although a very rare failure mode, it mainly occurs in ferrous materials with cobalt in their composition under high levels of radiation that typically occur in nuclear power stations.

ANSWERS TYPE :YES_OR_NO

WEIGHT MATCH : 21 MISMATCH : 0

This question is highly case specific in that it is associated with radiation embrittlement. This mainly occurs in ferrous materials with cobalt in their composition. However, due to its rarity as a failure mechanism, which is partly due to the levels of radiation required for this failure mode which occur in nuclear power stations. The actual match weighting is 21. If it were higher then by answering this question the expert system would conclude that radiation embrittlement was the only failure mode. This is very unlikely, especially in non-ferrous materials and materials with no cobalt in its composition.

52 TITLE What primary component group is your component

TEXT This means the main part involved in failure. For example if a shaft is a primary component group and if it has a small gear that was not involved in the failure then the gear is secondary. Shafts can fail by fatigue (rotational, bending, crack at 90 to axis) (torsional fatigue cracks at 45 to shaft axis) gross overload (brittle, no deformation cracks propagate across shortest route) (ductile, gross deformation, necking, cup & cone failure) Pipes can have distinctive failure modes, but are generally due to an initial defect, which can result from mechanical damage, fatigue cracks and material defects. Other failures occur from gross overload (secondary stress, internal combustion, or sabotage). A typical initial defect is most likely to be caused by a welding problem (lack of fusion, porosity, inclusions, lack of alignment, repairing, lack of penetration, etc.). Other different types of defects can be associated with environmental damage (corrosion internal and external, hydrogen-stress

cracking, external stress-corrosion cracking, internal sulphide-stress cracking, hydrogen blistering), fatigue, and other miscellaneous causes (erosion, wrinkles, etc.). Gears, includes spur, spline. helical, herringbone, cross-axes helical, worm, internal, rack, bevel, gears. Typical failures are broken gear teeth via overload, fatigue, wear, fretting fatigue, and on long axis gears, torsional overload and torsional fatigue.

ANSWERS TYPE : LIST

shafts, masts, poles, struts, rails, threads

bearings

pipes, tanks, & other fluid holding

components

gears

spring

welded components

lifting equipment (wire, chain, cable or hooks)

mechanical fastenings (rivets, nuts & bolts)

other

WEIGHT MATCH : 27 MISMATCH : 0

This question was developed after the evaluation stage and is the result of combining several other questions relating to different component groups. As the component group directly relates the propensity for different failure mechanisms, the match weighting is high. In further evaluation stages, the weighting might have to be increased. This question is also affected by the internal rules.

53 TITLE What is the primary process used in manufacture

TEXT Forging can improve the properties, weld up small crack and blow holes, refine the grain structure, eliminate oriented cast structure, and promote uniformity of material by diffusion of alloy constituents and the breaking up of brittle films of hard constituents or impurities, e.g. cementite in steel. This all helps in ensuring quality and reliability, if the processing was correct. Sometimes the initial material casting may be poor. This can lead to cracking in the material. This is generally shown up just after or during forging. Another major problem, is in poor alignment of the two forging heads. This can fold material over the parting line and can occur also when trimming. The cracks although small, and generally only show up after heat treatment, can be initiation sites for failure, such as by fatigue, and stress corrosion cracking.

Casting can have many effects on the properties of a material and these can lead to specific types of failures. If the material is worked again after casting such as by forging then the properties can be improved, but poor heat treatment and welding can reduce the material properties such as elongation to failure.

Poor machining such as blunt cutting tools or cutting speeds and feeds which are too high, can increase the surface roughness. This could mean poor fitting between parts and poor bearing surfaces which could lead to seizure; poor surface finish, and fatigue initiation from the rough surface undulations.

Welding is associated with an extensive number of failure mechanisms. These include cracking in or near the weld bead either due to poor welding technique, poor weld design, or operational conditions.

Poor grinding involves inducing cracks in to the surface, through heating, and excessive stress from trying to grind an over excessive amount of material.

Poor electric discharge machining processing can cause surface melting problems which lead to a thick and very hard (1100HV in steel) surface. This can causes cracking and premature failure.

ANSWERS TYPE : LIST
Forging
Casting
Machining
Welding
Grinding
Extrusion, or Drawing
Flame cutting
Rivetted seam
WEIGHT MATCH : 27 MISMATCH : 1

In a similar manner to question 53, this question has been developed after the evaluation stage, by combining together several manufacturing techniques questions. Also, in a similar manner, the weighting is high due to the importance of manufacturing techniques in failure.

54 TITLE What is the secondary process used in manufacture
TEXT To answer this question on secondary manufacturing processes required the user should state processes which have either been undertaken after or in addition to the primary manufacturing process. For example a component could first be forged and then machined. If the user answers this question the same as for the primary manufacturing question then this will re-emphasis the primary manufacturing process.

Forging can improve the properties, weld up small crack and blow holes, refine the grain structure, eliminate oriented cast structure, and promote uniformity of material by diffusion of alloy constituents and the breaking up of brittle films of hard constituents or impurities, e.g.

cementite in steel. This all helps in ensuring quality and reliability, if the processing was correct. Sometimes the initial material casting may be poor. This can lead to cracking in the material. This is generally shown up just after or during forging. Another major problem, is in poor alignment of the two forging heads. This can fold material over the parting line and can occur also when trimming. The cracks although small, and generally only show up after heat treatment, can be initiation sites for failure, such as by fatigue, and stress corrosion cracking.

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Poor grinding involves inducing cracks in to the surface, through heating, and excessive stress from trying to grind an over excessive amount of material.

Poor electric discharge machining processing can cause surface melting problems which lead to a thick and very hard (1100HV in steel) surface. This can causes cracking and premature failure.

ANSWERS TYPE : LIST
Forging
Casting
Machining
Welding
Electro-discharge machining
Surface hardening treatment
Drawing, or Extrusion
Flame cutting
Rivetted seam
WEIGHT MATCH : 16 MISMATCH : 2

This question was developed after evaluation and is used both to cover manufacturing processes not covered in question 53 " What is the primary process used in manufacture" and to combine several questions related to different failure mechanisms. The combined questions are 20, 35, and 38. The same extra text is also included in this question as in question 53, because the information might be required in both.

55 TITLE Did the failure occur at room or a higher temperature

TEXT At different temperatures different modes of failure will occur. Brittle failures, and hydrogen related failure can occur at temperatures below room temperatures.
Micro-biological corrosion generally occurs at temperatures below 65°C and below 125°C at all times. If you believe microbiological corrosion is a problem then select room temperature from the menu. The high temperature limits of materials, is a temperature above which creep has to be considered an important factor in design. Examples of these temperatures are detailed below in C°:-

Magnesium alloys	75	Titanium alpha alloy	250-350
Aluminium alloys	100	Cast irons	350
Coppers	120	Titanium alpha-beta	350-400
Brasses	150-200	Titanium beta alloy	300
Aluminium bronzes	250-400	Carbon steels	450
Phosphor bronzes	150	Cr-Mo Steels	550
Cupro-nickels	200	18% Cr, 10% Ni, Steel	600
Nickel silvers	150-200	25% Cr, 20% Ni, Steel	750
Titanium	250	Ni-Cr alloys	800

Ref. Bolton, William, "Hewnes Engineering Materials Pocketbook"1990, ISBN 0-434-90113
More information can be found in the latest edition of "Creep of Engineering Materials" by Iain Finnie and William R. Heller, Published by McGraw-Hill Book company.

ANSWERS TYPE : LIST :

Below room temp possible freezing

Room temperature

Above the materials high temp. limit

Above 0.6 of the melting temperature

WEIGHT MATCH : 19 MISMATCH : 0

This question was developed during evaluation so that it could combine several other temperature related question (3 and 39) together. Although temperature is highly important to the propensity of failure, due to problems in measuring local temperature, only an above average match weighting is used, i.e. 19.

56 TITLE What secondary component group is your component linked to

TEXT This means an associated part to the main part involved in failure. For example if a shaft is a primary component group and if it has a small gear that was not involved in the failure then the gear is secondary. Shafts can fail by fatigue (rotational, bending, crack at 90 degrees to axis) (torsional fatigue cracks at 45 degrees to shaft axis) gross overload (brittle, no deformation cracks propagate across shortest route) (ductile, gross deformation, necking, cup & cone failure) Pipes can have distinctive failure modes, but are generally due to an initial defect, which can result from mechanical damage, fatigue cracks and material defects. Other failures occur from gross overload (secondary stress, internal combustion, or sabotage). A typical initial defect is most likely to be caused by a welding problem (lack of fusion, porosity, inclusions, lack of alignment, repairing, lack of penetration, etc.). Other different types of defects can be associated with environmental damage (corrosion internal and external, hydrogen-stress cracking, external stress-corrosion cracking, internal sulphide-stress cracking, hydrogen blistering), fatigue, and other miscellaneous causes (erosion, wrinkles, etc.). Gears, includes spur, spline. helical, herringbone, cross-axes helical, worm, internal, rack, bevel, gears. Typical failures are broken gear teeth via overload, fatigue, wear, fretting fatigue, and on long axis gears, torsional overload and torsional fatigue.

ANSWERS TYPE : LIST:
shafts, masts, poles, struts, rails, threads
Bearings
pipes, tanks, & other fluid holding
components
gears
spring
welded components
Lifting equipment (Wire, Chain, cable or hooks)
Mechanical Fastenings (Rivets, Nuts & Bolts)
other
WEIGHT MATCH : 20 MISMATCH : 0

This question is similar to question 52 and was developed after the evaluation stage and is the result of combining several other questions relating to different component groups (springs, 22; gears, 31; pipes, 36; shafts, 46). However it is concerned with the secondary component groups and thus is used to both support question 52 and provide for the complexities of different component groups. This complexity is that there could be a combination of components making up the main component The match weighting is also similar to question 52 (i.e. 20)for similar reasons related to the importance of component groups in failure. This question is also affected by the internal rules.

57 TITLE What component group is NOT linked or like your component at all.

TEXT This means any component group not linked or involved in failure. For example If you had a gear failure, you know it had nothing to do with pipes as gears would never be linked to a high pressure steam pipe. This question is required to refine your answers without the need to ask many separate question on different component groups..

ANSWERS TYPE : LIST
shafts, masts, poles, struts, rails
Bearings
pipes, tanks, & other fluid holding
components
gears
spring
welded components
Lifting equipment (Wire, Chain, cable or hooks)
Mechanical Fastenings (Rivets, Nuts & Bolts)
other
WEIGHT MATCH : 20 MISMATCH : 1

This question has proved extremely useful in case base searching because it excludes many different failure cases. This was a result of the evaluation and it also has a high match weighting of 20. Yet, there is a possible problem with this question, in that fatigue can occur in springs and gears. While in the expert system's view point the possibility of fatigue is reduced which might not be actually ideal. Further evaluation could mean that the match weighting is changed.

58 TITLE Is the failure just surface damage or has it broken into parts
TEXT Surface damage relates to corrosion, pitting, discolouration, deformation, scratches, and surface melting (overheating and loss of coolant). When a part breaks in two, it is related to overload failures and fractures, breaking and cracking. When a part breaks into many pieces, it is related to rupture, explosion, implosion, spalling, delamination. When a part is unwantedly joined then the part is said to be seized, jammed or fused together

ANSWERS TYPE : LIST
Surface damage, and deformations
Broken into two parts,
Broken into many parts, shattered, multiple failures
The unwanted joining of parts, seizure
WEIGHT MATCH : 20 MISMATCH : 2

This question can detail a failure mode extremely well as it only required common terms to describe a failure in terms of the number of different parts. (Trethewey, 1996, private communication).

59 TITLE Has spalling or delamination of the surface occurred

TEXT Spalling and delamination is were the material's surface becomes detached from the main material mass. This could be due to impact, corrosion, poor extrusion, poor case hardening, selective leaching, and sub-surface defects.

ANSWERS TYPE : LIST

Spalling or delamination has occurred on the surface.

No Spalling or delamination has occurred on the surface

WEIGHT MATCH : 25 MISMATCH : 2

Due to its fundamental affect on failure, this question is given a high weighting.

60 TITLE Has the failure initiated within a thread run

TEXT This means from the start to the finish of a thread, i.e. its entire length. Threads are likely to fail through fatigue due to the increased stress concentrations at the sharp radius of a thread. Also through fretting and corrosion.

Ref: Metals handbook, 9th Ed., Vol. 11, Failure Analysis and Prevention, Failure of Mechanical fasteners, pp529-549, (1986)

ANSWERS TYPE : YES_OR_NO

WEIGHT MATCH : 17 MISMATCH : 2

This question is very case specific relating to the fatigue initiation in a thread run and thus there is an above average match weighting.

61 TITLE Would you consider the environmental ph. to be either:

TEXT Differences in pH levels can have an effect on the corrosion, embrittlement and biological attack rates.

ANSWERS TYPE : LIST

High, e.g. Alkaline

Normal, e.g. Water

Low, e.g. Acidic

WEIGHT MATCH : 14 MISMATCH : 2

This question is used to try to cover the many different environments which are very difficult to analyse. There are two previous questions covering the different environments, however these are complex as they ask for the exact composition of the environment. The above just asks for the pH value. This generic approach seems to work well but it might have to be split into two questions asking whether or not the environment is alkaline or normal and acid or normal. This is because some failure cases could be more serious in both acid and alkaline environments.

62 TITLE Has the component been cold worked?

TEXT Cold working involve any process which plastically deforms a material. This could be via a hammer, a rolling mill, cold forging, or even inadvertently by accidental bending.

ANSWERS TYPE : LIST:

Yes

No

WEIGHT MATCH : 10 MISMATCH : 2

This question has been separated from the main manufacturing question because many different manufacturing processes could either lead to or come from a cold working process. The reason for asking this question is to cover the different failure mechanisms related to cold working and the increase in hardness that can be caused by working. Presently the match weighting is average set at 10. However this could be set higher in future evaluations.

Chapter 10 Designing actions

10.1 Designing actions

Actions are solutions to failure problems that are defined in cases. On first impressions it can be envisaged that it is easier to define a case from the bottom up (Actions first), because, frequently the most clear-cut characteristic of the case is its action. Human experts are not restrained in identifying actions. Actions are usually the part of the case that can describe most clearly. In fact, the classic problem with human experts is that they can tell you exactly what to do, but have trouble explaining how they decided to do it. For example the consultant could say that weld decay is the problem. To solve this problem the solution is well known, but coming to that conclusion is considerably harder. So writing the action presents no problem, though to get the expert system to find the case through the questions and natural language description, is a lot more complex.

In the context of a failure analysis expert system application, an action is a solution to the problem where the problems are failure modes which are defined in cases derived from existing documentation and experiences. Once all the required failure modes are known, solutions and remedial actions can then be detailed. Therefore in the design of the failure analysis expert system it was far better to define the failure mode cases first, then the questions and rules to find the appropriate failure mode which was linked to the actions. Thus, from the list of failure mode cases, actions were derived. In general is at least one action for each failure mode. For instance, in the expert system, "Delamination and longitudinal split in extruded aluminium alloy mast" is an actions associated with the case "Delamination and longitudinal split in extruded aluminium alloy mast.". The failure mode is

represented by a case, and additional information about the condition is stored in action records. Thus action records are not required to diagnose a failure mode but provide extra information which to reduce the propensity for that failure mechanisms. However this idea of one failure mechanism, one case, and one action can fail especially when there are other solutions to the same failure mechanism or where there is a failure mechanism for which there are very few successful actions. This adds to the difficulty of developing an expert system.

As many actions are not case-specific, cases may share actions. Thus actions are defined once and reused as necessary. This helped speeds up development and uncluttered the system. For instance the action related to "Spalling problems" will be attached to several cases in which spalling may be a problem. Spalling occurs after surfaces have been brought together under a repetitive load in which the sub-surface shear strength is inadequate to withstand the shear stress to which it is subjected. This could be via a forge, rolling mill, hammering, etc. It can be seen that many cases could be linked to spalling, to which there is a common answer. In most case and actions, there are references related to further reading, as full descriptions are out of the scope of any expert diagnostic system. For example "Spalling occurrence is explained in Zener and Holloman, J. Appl. Phys., Vol. 15, 1944, p22. To solve the problem, try to reduce the loading on the component, increase the lubrication if and where possible, and remove any damaged components from service before it causes injury. Also where and when possible the core hardness or case depth should be increased" Thus the actions within the failure analysis expert system helps the engineer to diagnose, but not prescribe a set ideal answer.

As many cases share actions, it is useful to think of the "actions" as records that are simply associated with various cases for informational purposes. The records do not have to contain prescriptive solutions, but general suggestions to reduce the propensity for failure and increase general reliability For instance, "Increase the fatigue strength by surface treatment" or "Bacteria, fungus, or macro-organisms and their corrosive effects" is an action that might apply to any number of cases. During development it was found that it was necessary to edit the actions to adapt an action so that it could be used by several cases.

In addition to information on solutions and suggestion to reduce the propensity for failure, actions require references, (i.e."British Engine Boiler and Electrical Insurance Co. Technical report 1965 Vol.VI pp76-80)

In considering the amount and type of information to provide in actions, it is important to know what is the users initial level of expertise. For example, a highly qualified engineer would require far less information than an engineering student. A general rule for a good action presumes that the users know nothing and gets right into the details of how to solve the problem. With the correct design of the text layout the engineer can skip the introduction and get to the main details. The text has been so designed and follows ideas found in James Hartley's book "Designing Instructional Text" (1994) in that actions should not be simply a restatement of the problem. Rather an action is a prescription for solving a problem. As such, the action tells both what to do and how to do it.

It was found very important to emphasize the difference between similar actions: If two actions were similar, but not the same, then the difference in the titles of the actions were stressed. For example consider the following actions:

50 "Temper Embrittlements (Ductile to brittle transition type fractures)"

51 "Radiation Embrittlements (Ductile to brittle transition type fractures)"

Although these are both related to ductile to brittle transition type fractures, these are separate cases and thus have been separated into explicit actions. Sometimes it can be more accurate creating two new actions and using the one that is most appropriate:

Some actions run other software programs, via the commands that have been entered in the action's Graphic Browse fields. For example, below is an action that starts up another expert system program (tmodel.exe).

```
59      TITLE "Crevice Corrosion Engineering Guide (Nickel development Institute)"
BROWSE GRAPHIC          TOOLBOOK
BOOK : "run"            PAGE : "c:\\cbrx13dk\\guide\\tmodel.exe"
```

In developing and evaluating, it was found important to review cases that have more than four actions due to the possibly of more than one failure mode within the case. The expert system software works better when cases identify single problems with single solutions. However, there are plenty of situations in failure analysis where a failure problem has two or three possible solutions/actions associated with it. When this occurred it either indicates that the cases themselves might not have been decomposed into individual problems, or it may mean that the actions have been broken up too finely.

10.2 Conclusions

1. These action records come either in a simple text format or in a multimedia electronic book.
2. Many actions are not case-specific, so cases may share actions that are defined once and reused as necessary. This speeds up development and un-clutters the system.
3. An "action" can be thought of as a convenient data record that associates additional information with the case.
4. The amount of information within actions requires a balance between just enough and not too much information. The balance depends on the use's past understanding.
5. Using a hypertext format, the text was designed so that actions were not simply a restatement of the problem, rather a prescription for solving a problem, so actions tell both what to do and how to do it.
6. Thus the actions within failure analysis expert system helps the engineer to diagnose, but not prescribe a set ideal answer.

10.3 List of Actions

Many of the actions are presently left blank, this is due to the considerable task in getting accurate and detailed information for each action. However, these blank actions indicate the importance and requirement for further remedial actions and this is an area in which further work is required. Some of the actions are so general that only considerable analysis of the actual user requirement to get the correct and relevant information will produce a useful action. An example is action 2 "Improve the manufacturing process and non- destructive testing". In these situations, until the complete development of these actions, reference must be made to the relevant failure case in the expert system.

1 TITLE Use a proper grinding procedure and post grinding inspection

2 TITLE Improve the manufacturing process and non- destructive testing

3 TITLE Avoid bolted or rivetted joints unless the metals are coated

4 TITLE Close or seal existing crevices

TEXT Close or seal existing crevices by the use of a flexible silicone sealant or other sealing method such as nut-lock for screw threads, etc.

5 TITLE Inspect and remove deposits frequently

6 TITLE Use solid nonabsorbent gaskets or seals

7 TITLE Improve your welding procedure

8 TITLE Increase the fatigue strength by surface treatment

TEXT The fatigue strength of parts which are subjected to reverse bending or torsional stress, such as springs, keyways, etc, can be considerably increased by introducing compressive internal stresses into the surface zone, which is subject to the highest stresses. This can be achieved by surface hardening particularly by nitriding or by sand or shot blasting and also peening. The idea is that the compressive stress at the surface must be first overcome during loading before the surface zone comes under tensile loading, which opens up cracks. See remedial action & solution panel on "General overload failure prevention (& fatigue failure prevention)" action 19

9 TITLE Change the welding consumable to stop corrosion problem

TEXT Change the welding consumable to the same material as the bulk material. This means a consumable of the same alloying content (or higher alloy content to allow for dilution in the weld pool) as the bulk material, so there is no electro-potential difference between the interfaces. Typical problems relate to the fact that the alloying additives in the electrode coating can be broken off or the wrong grade of electrode selected.

10 TITLE Replace spring with a higher quality spring

TEXT See B.S.1726, Coil springs, B.S. 2056 Stainless Steel wire for springs.

11 TITLE Remove surface and sub-surface defects to improve fatigue strength

TEXT Remove surface and sub-surface defects to improve fatigue strength. This can be done by grinding or gouging out the defect and welding over the defect. If the defect is a crack then a hole can be drilled at the advancing crack front to reduce the stress concentration. If the component is a critical component then replace the component with a new and or improved new component.

12 TITLE To stop stress corrosion cracking

TEXT Stress corrosion cracking (SCC) occurs when the following three conditions are simultaneously fulfilled. (1) The material must have a particular tendency to stress corrosion cracking. (2) Static tensile stresses must be present, whether applied or internal, which give a stress intensity factor at or above the threshold stress intensity factor for SCC (KISCC). (3) There must be an attack by some agent capable of initiating stress corrosion cracking in this particular material. Therefore SCC can be eliminated by removing one of the above situations. So if the material is changed to a more corrosion resistance material or tensile stresses are removed, or the corrosive attacking agent is removed, SCC can be stopped. The removal of internal stresses can be achieved by careful annealing and production processes that keep the residual stresses to a minimum. i.e. sharp cutting tools and post-weld heat treatment. Alternative materials for the 300 series stainless steel are the nickel-iron-chromium alloys such as Inconel 625 or Inconel 825, which have good resistance to general corrosion and stress-corrosion cracking. Alternative a non- metallic material could be used in the most serious case, but this depends on the loading during service. Ref:- "Corrosion for students of science and engineering", K.R. Trethewey & J Chamberlain, Longman, 1988.

13 TITLE Reduce mechanical wear and turbulence corrosion problems

TEXT Turbulence can cause localised rupture failure and the removal of the natural protective layer in a pipe. A potential difference between surroundings and exposed metal (anode) causes corrosion, accelerated by dispersed solids particles in flow (water, gas). To reduce mechanical wear and turbulence corrosion problems in a pipe you must avoided sharp transitions and abrupt changes in cross section so to reduce local turbulence. Filter the flow to remove solids and other particulate if possible. With fluids (water, etc) these should be

degassed and cleaned to reduce erosion particularly in the case of soft water which takes up oxygen and carbon dioxide very readily, so becoming particularly aggressive. Ref:- Metals handbook 9th Edition, Volume 11,Failure Analysis and Prevention, American Society of Metals, ISBN 0-87170-007-7, Pages 695-706

14 TITLE Reduce shock loading in towing cables

TEXT The reduction of shock overload loading which causes failure in cables can be achieved by: Firstly check that the load to be pulled has as much drag reduced as possible. This could include the reduction of weight and drag due to wind resistance, and friction in wheels, etc. Secondly, if possible install a constant tensioning device that takes account of loads in all axes (X,Y,Z). Ref. Handbook of case histories in failure analysis Vol.2 A.S.M Int. , ISBN: 0-87170-495-1 Page 24-27.

15 TITLE Improve electric discharge machining processing

TEXT Poor electric discharge machining processing can cause surface melting problems which lead to a thick and very hard (1100HV in steel) surface layer. This can cause cracking and premature failure. Therefore maintain the correct current densities and avoid short circuiting with subsequent high temperature melting. Ref. Handbook of case histories in failure analysis Vol.2 A.S.M Int. , ISBN: 0-87170-495-1 Page 28-29.

16 TITLE Processing-induced fatigue fracture in aluminum alloy component.

TEXT Poor processing parameters in aluminum alloy can induced fatigue fracture. This processing could include multiple plating, chemical etching, anodising, etc, which are done to improve the corrosion resistance. The idea is to thicken the surface film and produce a hard, compact, strong and tightly adherent layer. When multiple plating is undertaken, this is for the same reasons, i.e. to improve the corrosion resistance. This sometimes involves nickel plating in which, after each plating cycle, an etching cycle is included to improve (flatten and improve adherence) the surface ready for plating. Poor processing at the different stages especially during etching can produce pits in the surface. This is called pitting corrosion. These pits are initiation sites for fatigue fracture. The fatigue failure surface is flat, shiny, with reflective facets. This is not helped by baking or heat treatment processes which can reduce mechanical strength, so this has to be highly controlled and recorded.

17 TITLE What to do for subsurface defects

TEXT Subsurface defect could include the following:-

(1) Constituents harder than the background or matrix which stand out in relief, e.g. phosphides in cast iron.

(2) Blowholes and spongy places, which should be confirmed by focussing with a microscope on the side or bottom of the cavity.

(3) Non-metallic inclusions: (a) Manganese sulphide(dove grey masses), round in castings, elongated in forgings; (b) iron sulphide (brownish yellow), in films around grain boundaries; (4) slag, Mn-silicate has greenish tinge, iron-silicate is black Al_2O_3 occurs as hard rounded grains; (d)copper oxide (blue); (e) graphite in cast iron (grey)

(5) Changes in properties within a material, this could be due to an interface between a heat treated zone and a non-heat treated zone, such as in a internal stress rupture in a gear tooth, Other interfaces can also affect internal properties such as plating, case hardening, nitriding, etc.

The nature of the defect determines what can be done, but the following are guide lines:- - Ensure that your manufacturing processing has the right parameters set on the different machines - Ensure proper inspection of the material. This could be via Non-destructive testing using techniques such as Magnetic induction, Ultra-sound, X-ray, Radiography - Ensure that the materials comply with the specification and are suitable for the usage. Good communications with your suppliers will help especially if their process is producing poor quality materials.

18 TITLE Overload failure in a sand cast aluminum-base alloy

TEXT Overload failure in a sand cast aluminum-base alloy, this can be seen by extensive cracking and evidence of substantial deformation in the region around stress concentrations such as holes, corners, keyways. Generally material (LM6) is in specification. To prevent such a failure you have to increase the strength, especially around stress concentration, such as holes, corners, etc. This can be done in several ways; (i) If space and weight considerations permit, increasing the thickness of section and or webs at and around the high stress concentration area, with a generous fillet blending into the web could lower the effective stress level. (ii) Introduce residual compressive stress at the bore hole. This is done by

forcing oversize plugs through a hole, stretching the surrounding metal until it yields plastically. Once the plug has passed through, non-yielded material closes in elastically to create a residual compressive stress in the material near the bore. The residual compression offsets tensile service stress and thereby increases resistance to fatigue failure. (iii) Finally if the cost constraints permit change the material so as to have a higher strength material and or use some kind of heat treatment. If your material is aluminum alloy (LM6M) then change to C-355 and heat treat to T6 condition. Use chills in the mould to maximize the freezing rate and to minimize the size and adverse morphology of silicon plates. Also using plaster moulds up to 14kg will increase the tensile strength (303 MPa) and the yield strength (228MPa). Ref; Handbook of case histories in failure analysis, vol. 2, ASM. international, ISBN 0-87170-495-1

19 TITLE General overload failure prevention (& fatigue failure prevention)

TEXT Overload failure in a material can be seen by extensive cracking and evidence of substantial deformation in the region around stress concentrations such as holes, corners keyways. Generally material is in specification and in good condition. Fatigue failure is caused by a cyclic stress which does not have to be as high as the yield stress, and will involve less deformation than an overload failure. To prevent such a failure you have to increase the strength, especially around stress concentration, such as holes, corners, etc. This can be done in several ways; (i) If space and weight considerations permit, increasing the thickness of section and or webs at and around the high stress concentration area, with a generous fillet blending into the web could lower the effective stress level. (ii) Introduce residual compressive stress at the bore of each bolt hole. This is done by forcing oversize plugs through a hole, stretching the surrounding metal until it yields plastically. Once the plug has passed through, non- yielded material closes in elastically to create a residual compressive stress in the material near the bore. The residual compression offsets high tensile service stress due to the stress concentration effect of the hole and thereby increases resistance to fatigue failure. (iii) Finally if the cost constraints permit change the material to a higher strength material and or use some kind of heat or surface treatment such as nitriding, carburising and tempering. Ref; Handbook of case histories in failure analysis, vol. 2, ASM. international, ISBN: 0-87170-495-1

20 TITLE Reduce mechanical wear and turbulence erosion problems

TEXT Turbulence can cause localised rupture failure and the removal of the natural protective layer in a pipe. In corrodible materials (steel, etc)a potential difference between surroundings and exposed metal (anode) causes corrosion but in non-corrodible materials such as plastic, copper, lead, erosion is the first problem, although if the protective layer is broken down then corrosion is a problem (Stainless steel). Typical protective layers are stable metallic oxides on metals, and organic coatings such as plastic, paint, etc. Erosion is accelerated by dispersed solid particles in flow (water, gas). To reduce mechanical wear and turbulence corrosion problems in a pipe you must avoid sharp transitions and abrupt changes in cross section so to reduce local turbulence, i.e. U-bends, elbows, flanges. Filter the flow to remove solids and other particulate if possible. With fluids (water, etc) these should be degassed and cleaned to reduce erosion particularly in the case of soft water which takes up oxygen and carbon dioxide very readily, so becoming particularly aggressive. Erosion damage is most likely to occur at high velocities (in excess of 2.13m/s (7ft/s) for steel and this changes for other materials depending on their hardness), first at locations of flow change, then at other areas. The flow velocity, V for water, can be determined by the equation:-(mass/3600 = density * Velocity) The simplest method to reduce the flow velocity is to increase the pipe cross sectional area. Ref:- Metals handbook 9th Edition, Volume 11, Failure Analysis and Prevention, American Society of Metals, ISBN 0-87170-007-7, Pages 695-706 and 163-171

22 TITLE Spalling problems

TEXT Spalling occurs after two surface have been brought together under a repetitive load in which the subsurface shear strength is inadequate to withstand the shear stress to which it is subjected. This could be via a forge, rolling mill, hammering, etc. This is a result of contact fatigue and high contact stresses. Cracks occur at subsurface locations such as inclusions, where the contact stresses are maximised. If there is a sliding action, such as a bearing or contact roller, then the crack may initiate at the surface. These cracks can form pit, but if several pits join together or a crack runs parallel to the surface, large spalling defects occur. These are associated with surface hardened components such as gears at the case/core interface. Thus by decreasing the case depth and making the core tougher and less hard this problem could be reduced, but erosion wear rates would be increased, making erosion wear

more of a failure problem than spalling. Thus where and when possible it is better to increase the case depth or core hardness.

In race ways or other flat surfaces the spalling failure looks like craters with sharp edges, generally steep walls, and more or less flat bottoms. In hammers and other impact tools (see case and remedial action on "Case crushing") such as dies, punches, and bits, a greater danger is failure at the subsurface causing a chip of metal to be ejected during service. Hammers are generally made of hardened carbon steel (approx. 0.85% C) in the tempered martensite microstructure state. The high strain rate of an impact causes bands of intense adiabatic unstable shear. (Zener and Holloman, J. Appl. Phys., Vol 15, 1944, p22, concluded the bands were martensite formed by high temperatures resulting from the concentration of shear strain, which changed the structure to austenite, that was rapidly quenched by the surrounding material.) The bands are very hard and brittle, where the surrounding materials hardness has been lowered by absorbing the heat of the shearing, thus tempering. To solve the problem, try to reduce the loading on the component, increase the lubrication if and where possible, and remove any damaged components from service before it causes injury. Also where and when possible the core hardness or case depth should be increased.

Ref: Metals Handbook, 9th edition, Vol. 11, "Failure Analysis and Prevention" pp 9, 89, 133-134, 341, 491, 501

Handbook of Case Histories in Failure Analysis, (1992), ASM International, Transfer gear shaft **Vol. 1** pp299-300, Ball-peen hammer **Vol. 2** pp467-469, ISBN: 0-87170-078-6.

23 TITLE Cracking at a parting line in a forging.

TEXT Although forging can improve properties, cracks can occur at a parting line in a forging due to poor alignment of the two forging heads (die set). This can fold material over the parting line and can occur also when trimming, because trimming close to the component can produce tearing along the parting line. The cracks although small, generally grow and show up after heat treatment. These cracks can be initiation sites for failure, such as by fatigue, and stress corrosion cracking. A large grain structure and high temperature scale can sometimes be observed around the parting line, which is not seen in other parts of the forged components. This failure is associated with carbon and low alloy steel and with vanadium contents of less than 0.06%. Another way in which folds can occur is due to abnormal material flow. This is generally caused by poor design of the die set as well as poor alignment.

In conclusion, the misalignment of the die set could be due to poor maintenance on the hammer, inexperienced operators, and poor design of dies. Therefore it is important to check the alignment of the die set and make sure that personnel with adequate skill set up the die set to the required procedure. If the forging was correctly aligned then the initial material casting could have been of poor quality. This can lead to cracking in the material. This is generally shown up just after or during forging. Khlefe A. Esaklul,'Handbook of case histories in failure analysis, vol. 2', American Society of Metals, ISBN:0-87170-495- 1, Cracking on the parting line of closed-dia forging, by A.J. Koprowski, page 463-466, 1993

24 TITLE General creep failures in materials

TEXT Creep is the slow plastic deformation of metals under a constant stress. The stress could be very small, ie its own weight. Typical creep failure could be in the following situations :-

(i) Soft metals used at room temperature, such as lead pipes and white metal bearings,

(ii) Superheated steam and chemical plants operating above 420 C.

(iii) Gas turbines (jet engines) working at high temperatures.

Creep is very time/temperature dependent for a given material. A designer is concerned with creep rate which is the strain per unit time, de/dt of a material. It may only be a fraction of a percent per month. However, in a superheated steam boiler, steel tubing may be in service at 650 C. (1200 F.) for years. The steam pressure at these temperature is very high, so that the steel is never free from stresses. Thus, even 0.01% strain per day of service is not tolerable. Creep rates are faster in fine-grained materials (polycrystalline) materials than in the same material with less grain boundary area per unit volume. When the temperature is high enough to permit atom movements, the grain boundary facilitates the atom relocation from sites of high stress to positions of low stress. This means that at high temperature coarse-grained materials are stronger than fine-grained materials. Recent development in the aerospace field have led to the developments of single crystal components. They have no grain boundaries for slippage to occur and so have high strength at high temperatures and extended service lives. A typical use for single crystal components is turbine blades. Therefore to increase the creep life either use single crystal material if cost and availability allows or introduce alloying elements into the material to increase the strength, by forming precipitates at grain boundaries to stop atom movement. Additionally the stress could be reduced by increasing the cross

sectional area, but this very much depends on the application. Turbines require small clearances so an improvement in material would be best, where high temperature piping, on the other hand, dimensional tolerance is relatively unimportant, and the condition to be avoided is rupture within the design life. Whatever is done the hazards and inconveniences associated with fracture must also be evaluated. Also consideration towards corrosion and oxidation, fatigue and damping capacity, and irradiation, while important in themselves, may also affect creep properties. In the majority of cases, designs are based on a mixture of short term properties(yield strength, tensile strength) and creep properties (rupture life, creep rate), but as most applications are in service at ambient temperatures creep is of no problem in design. With high temperatures, designs may have to be wholly based on creep considerations. For intermediate ranges of time or temperature, the designer will have to make decisions on the relative importance of both short-term properties and creep considerations. The high temperature limits of materials, is a temperature where creep has to be considered an important factor in design. Examples of which are detailed below in degrees C:-

Magnesium alloys	75,	Aluminium alloys	100,
Coppers	120,	Brasses	150-200
Aluminium bronzes	250-400,	Phosphor bronzes	150
Cupro-nickels	200,	Nickel silvers	150-200
Titanium	250,	Titanium alpha alloy	250-350
Cast irons	350	Titanium alpha-beta	350-400
Titanium beta alloy	300,	Carbon steels	450
Cr-Mo Steels	550,	18% Cr, 10% Ni, Steel	600
25% Cr, 20% Ni, Steel	750,	Ni-Cr alloys	800

Ref. Bolton, William, "Hewnes Engineering Materials Pocket Book" 1990, ISBN 0-434-90113 More information can be found in the latest edition of "Creep of Engineering Materials" by Iain Finnie and William R. Heller, Published by McGraw-Hill Book company.

25 TITLE Steel creep failures by graphitization / spheroidization

TEXT In addition to general creep failures, when steel is used at high temperatures, additional problems of graphitization and spheroidization make the creep situation worse. Graphitization is the decomposition of pearlite into ferrite and carbon (graphite) that

sometimes occurs in carbon or carbon-molybdenum steels subjected to moderate overheating for long periods of time. This microstructure change can embrittle steel parts, and reduce strength and creep resistance. Pearlite decomposes by either graphitization or spheroidization. Both mechanisms are temperature-dependent and occur at temperatures in the range 427 to 732°C (800-1350°F). Graphitization usually occurs at temperatures below 550°C (1025°F); formation of spheroidal carbides usually occurs at higher temperatures. Tubing , piping, and other components exposed to temperatures from about 425 to 550°C (800 to 1025°F) for several thousand hours are most likely to be damaged by graphitization See action number 24, for more information on general creep failure. More information can be found in "Creep of Engineering Materials" by Iain Finnie and William R. Heller, Published by McGraw-Hill Book company. Ref. Bolton, William, "Hewnes Engineering Materials Pocket Book" 1990, ISBN 0-434-90113

28 TITLE Corrosion fatigue

TEXT Corrosion fatigue failure is caused by a combination of fluctuating stress and an aggressive environment, which increases crack growth and reduces fatigue life, although the loss of metal by corrosion may be negligible. Corrosion fatigue cracks always initiate at the surface unless there is a near subsurface defect which initiates a fatigue crack or acts as stress concentrations. As a short crack in the region from 10 to 500 micrometers long, depending on the material, the crack growth rate is very high under conditions of corrosion, higher than for large cracks. This is due to the electro-chemical effects at the tip of the crack. Therefore it can be seen that the electrochemical effects in corrosion can initiate and propagate cracks. Crack growth rate is also enhanced by increased in temperature, mean, peak, frequency & amplitude of stress ranges, as well as by corrosive media. The fracture surface is difficult to distinguish although the origin of the corrosion fatigue is often surrounded by beach marks or crack arrest lines. Often there are several origins when pitting is involved. Sometimes the origin has been wiped out by a compressive stress cycle, and or corrosion, which is greater in the areas with the longest exposure to the environment. Other features that can be observed, if corrosion has not obscured them are secondary cracks, pits, and fissures, adjacent to the main origin, also striations, tyre tracks, plateaus separated by shear steps, tear ridges, or both. Crack initiation and propagation can start for other reasons such as stress corrosion cracking (SCC), which is similar to corrosion fatigue but SCC

generally only occurs when the stress-intensity factor (KIscc) is exceeded. Corrosion fatigue and mechanical fatigue can be distinguished by the fact that several corrosion fatigue cracks can form and propagate simultaneously along parallel paths, whereas mechanical fatigue, like corrosion fatigue, might have multiple initiation sites but in a short distance one crack becomes dominant, or several cracks join to form a single front. Corrective Measures. (i) Reduce stress levels and stress fluctuations. This will involve redesigning of the component, to increase cross-sectional areas, reduce stress concentrations, and introduce compressive stress at the surface. This could be by heat treatment, shot peening/blasting, nitriding, and by selective yielding (pressure vessels) (ii) Use a different material to increase the corrosion strength,

Endurance Limit+/- N/mm^2 Steel Tensile at 5 x 10E7 cycles

	Stress N/mm^2	Air	Fresh Water	Salt Water
0.16% C steel	453	247	138	62
3.7% Ni Steel	625	625	340	110
Stainless Iron	618	378	263	200

(Stainless Iron => 12% Cr)

Ref. E.C. Rollason, Metallurgy for Engineers, 4ed., Arnold, 1973, pp31.

As seen above, an increase in the alloy content can increase the corrosion fatigue strength, when taking into account the medium in which the component is immersed. Adding alloying materials to just increase the strength will have a small impact on the component life, but there is greater effect by increasing the fatigue strength and corrosion resistance. Alternatives to alloying could be by galvanic protection (galvanizing, anodic protection)or by altering or removing the corrosive environment (painting, greasing, change of environment). If it is suspected that your component is susceptible to corrosion fatigue, then inspect, for pitting and other corrosion damage (cracks, etc) and either remove the pits by polishing or replace the component with an improved design. Also remove corrosive agents from the environment, such as water vapour, water in oil lubrication, salts, and aerate the environment around the component. For further details see "Metals Handbook, Failure Analysis and Prevention, Vol. 10, 8th edition, By the American Society for Metals, 1975. "Metals Handbook, Failure

Analysis and Prevention, Vol. 11, 9th edition, By the American Society for Metals, 1986. pp252-262

30 TITLE Liquid-metal embrittlement of steel or copper alloys by liquid metals

TEXT Liquid-metal embrittlement (LME) or Liquid-metal induced embrittlement (LMIE) is generally a brittle intergranular failure, with little indication of crack branching or striations to indicate slow crack propagation, in a normally ductile metal when coated with a thin film of liquid metal and stressed. In some special cases ductile and or transgranular failure can occur. The crack growth is generally very fast and initiation occurs at the solid-liquid metal interface. Steel is LMIE by mercury, gallium, sodium, indium, lithium, tin, cadmium, lead, zinc, antimony, tellurium, copper. Copper is LMIE by mercury especially, but also by antimony, cadmium, lead, tin, lithium, sodium, bismuth, gallium, indium, thallium. This is increased when copper is alloyed with aluminum (aluminum bronze), and zinc (brass) especially with mercury, which is one of the most commonest form of LME in copper alloys (brass 70Cu,30Zn). The loss of ductility from LME manifests itself as a reduction in elongation to failure, a reduction in fracture toughness and a reduction in area at failure, although the bulk and work hardening properties stay approximately the same.

Generally, two pre-requisites have to exist before LME occurs, which are as follows:

(i) There must be intimate contact or wetting of the solid metal by the liquid metal at the crack tip for the brittle fracture to continue as a LMIE type fracture. When there is no liquid metal at the crack tip, then the crack is propagating by other means, such as cleavage, shear, and microvoid coalescence, though after fracture the surface can then become coated in the liquid metal.

(ii) The solid metal must be sufficiently stressed to produce (localised) plastic deformation. The required stress level could be reached at notches, inclusions, grain boundaries, and secondary phase particles, where stress concentration or residual stresses can produce high stress levels with little or no plastic deformation. The failure surface is covered by a very thin layer of the liquid metal, from a few atoms to a few millimetres thick. This can be very hard to detect and could require some form of X-ray analysis or chemical analysis to find. In this section on LMIE, not all situations can be covered, as the literature is sparse, but it can be said that most pure and industrial alloys undergo some form of LMIE depending on the combinations of metal, liquid, temperature and stress level. Any reader interested in LMIE,

should consult the following article:- Ref:- P.J.L. Fernades, R.E. Clegg, and D.R.H. Jones, "Failure by Liquid Metal Induced Embrittlement", Engineering Failure Analysis, Vol. 1, No. 1, pp 51-63, 1994, Elsevier Science Ltd. And the following books:- American Society of Metals, "Metals handbook" 9th ed., Vol. 11, pp225-238, Nov. 1986. British Engine Boiler & Electrical Insurance Co. Technical report 1965 Vol.VI pp76-80 (Also Volume III, page 161; Volume IV, page 16.)

31 TITLE Increase the strength of a given material

TEXT If the material of a component cannot be changed you can increase the strength of the material by different processing methods. Some of these are listed below, although this is are not a complete list of all the processes, they are an indication of where to start.

CAST MATERIALS Cast materials have no directional properties, because of the equi-axed grains in the microstructure, unless there has been either fast cooling in the mould or some form of heat treatment. Fast cooling produces a larger number of heterogeneous nuclei and thus smaller equi-axed crystal grains which are stronger because grain boundaries are effective barriers to dislocations, but can produce lines of segregation parallel to length axis and elongated grain growth perpendicular to the length axis, within the casting, especially with thin sections. Segregation generally occurs at the centre line but can also occur at the corner. This leads to weakness in the casting. To reduce these problems the designer should avoid abrupt changes in section and massive junctions; avoid recessed parts or undercuts; ensure the correct thickness of thin sections for rigidity and to stop solidification cracking ensure correct venting.

In steel castings fine grains are preferred. This can be seen by comparing fine grained steel (3-16 grains per square cm)(18-96 grains/in^2) with coarse grained steel (0.2-2 grains per square cm)(1.2-12 grams/in^2):

(i) Enhanced notch-bar toughness in plain steels, but increase is less in alloy steels.

(ii) Shallower hardening; less tendency to warp and crack.

(iii) Carburises less deeply; absence of grain growth in core permits single quench from the carburising temperature.

(iv) Less tendency for cracks to originate in flash trimming of forgings.

(v) Mass production machining is more difficult.

(vi)Deterioration by quench and strain ageing is reduced.

Greater standardisation can therefore be obtained by using a steel with an inherent grain size suitable for a particular purpose. To improve the quality and strength of a cast material component, the processing of the material can be changed to include hot or cold working. Hot working involves processes such as; Rolling; Forging; Extrusion; Drawing; Piercing; Spinning. Hot working involves plastic deformation of a metal at a temperature above its recrystallisation temperature

32 TITLE Hydrogen embrittlement failure of maraging steel bourdon tubes

TEXT Ref:- B.G. Mellor,"Hydrogen embrittlement failure of maraging steel bourdon tubes", Engineering Failure Analysis, Vol. 1 No.1, pp.65-75, 1994, Elsevier Science ltd.

The paper details this problem and a summary is given below of the discussion and remedial actions. Intergranular crack found, initiated on the internal bore of the tube, running axially & circumferentially, propagating to the external surface. Although the remains of low melting point alloy were found on the bore of the tubes, Energy Dispersive X-ray Spectroscopy did not detect the elements of low melting point alloy either on the fracture surface or in the cracks. This indicates that the mechanism responsible for the cracking is not liquid-metal embrittlement by the low melting point alloy. The intergranular, gaping morphology of the cracks together with the presence of corrosion pits therefore suggests that hydrogen embrittlement has occurred. Maraging steel is well known for hydrogen embrittlement even in mild corrosive environments, e.g. moist air. In the presence of sulphur, carbon (carburised oil), poor surface finish and stress (applied or residual) hydrogen embrittlement is promoted.

Remedial measures:

In this actual case the procedure for filling and melting out of the low melting point alloy was modified to ensure a clean alloy surface. Endoscopic inspection is used to ascertain whether any remains of low melting point alloy are present in the bore of the tube after the melting out operation. All oil contamination is eliminated before heat treatment and the heat treatment is carried out in a vacuum. Also the surface finish was improved. In addition to this in a general case, it is important that all impurities are removed before heat treatment and after the melting

out of the low melting point alloy. Also the stress and surface roughness must be kept to a minimum.

33 TITLE Sulphide stress (sour) corrosion cracking

TEXT Sulphide stress (sour) corrosion (brittle) cracking occurs with oil & gas due to hydrogen sulphide gas, hydrogen sulphide, & water. More corrosive when moisture, oxygen and carbon dioxide are present. Seen as pitting corrosion & corrosion-erosion. Generally occurs in high strength materials with the application of external stresses. Increases at room temperature. Susceptible materials are stainless steel & Nickel alloys.

The following articles may be useful.

Chen, S. H.; Yeh, R. T.; Cheng, T. P.; Yang, I. J. (1994),"Hydrogen sulphide stress corrosion cracking of TIG and laser welded 304 stainless steel", Corrosion science, Volume 36, Number 12, pages: 2029 ISSN: 0010-938X,BL Shelfmark: 3476.500000

Habib, K.; Husain, A. (1994)," Stress corrosion cracking of copper-nickel alloys in sulphide polluted natural seawater at moderate temperatures", Desalination, Volume 97, Number 1/3, Pages: 29, Proceedings of the IDA and WRPC World Conference on Desalination and Water Treatment, ISSN: 0011-9164, BL SHELFMARK: 3555.700000

Azuma, S.; Kudo, T. (1991),"Crevice Corrosion of Corrosion-Resistant Alloys in Simulated Sour Gas Environments.", Corrosion, Volume 47, Number 6, Pages: 458, June1991, ISSN: 0010-9312

Schmitt, G. (1991)," Effect of Elemental Sulfur on Corrosion in Sour Gas Systems", Corrosion, Volume 47, Number 4, Pages: 285, April 1991, ISSN: 0010-9312

34 TITLE Fatigue calculations

BROWSE GRAPHIC

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35 TITLE To reduce excessive wear on a single gear or sprocket

TEXT Excessive wear on a single gear or sprocket is generally caused by the fact that the other surfaces to which this worn part interlink are harder. This hardness difference could be due to the following; If the materials are the same then poor manufacturing of the worn gear i.e. heat treatment (case & core properties, case hardening, tempering), ; If different materials then poor materials selection i.e. one harder than the other; These effects can be solved by matching the hardness between the gears by some form of case hardening or by using a stronger/harder material. This simplistic approach does not take into account the most difficult factors which are the service conditions of high stress, misalignment, which will increase the effects of poor manufacture and materials selection. With this mode of failure, lubrication is a major consideration especially with foreign materials within the lubricant, and a low level of lubrication, in which case a check of the seals, pumps, and other gears should be undertaken. Foreign materials which should be washed away and filtered out can end up on the surface of a gear/sprocket which gives the surface the properties of a grinding wheel, and thus wear the other gear/ sprocket.

36 TITLE Adhesive wear

TEXT Adhesive wear occurs on sliding surfaces when the pressure at the point of contact becomes high enough to cause plastic deformation and adhesion between the surfaces. The plastic deformation due to the pressure causes heat build up at the contact points. This heat changes the surface microstructure and causes a glassed surface. As the frictional heat increases, the surface becomes softer so plastically deforms to a greater extent, and thus the adhesive properties between the two surfaces increase. This completely changes the surface microstructure to the point where the two surfaces weld together at selective points and then are pulled apart lifting some material off one of the surface to produce what is called Galling. The welded particles are generally harder than the original metal due to the contact pressure and rapid cooling in the lubricant. These hard particles then cut into the contact surface, as if one of the gears has become a grinding wheel. If adhesive wear continues then gear failure will occur as tooth failure and excessive surface pitting. In some cases where another component has failed or there are some foreign bodies in the area of the gears, i.e. a gearbox, then these particles can attach themselves to one of the contact surfaces and thus start the events leading to the adhesive wear failure. To reduce the likelihood of adhesive wear it is important to reduce the contact stresses, initially by using of the correct viscosity grade of

lubrication to produce hydrodynamic lubrication. If this is unsuccessful then use a harder gear to resist plastic deformation. This could be done by a case and core hardening process and a harder material specification. If this is not possible then increase the contact surface area by changing the gear design. ref:- L.E. Alban, "Systematic Analysis of Gears", American Society for metals, 1985.

37 TITLE Internal stress rupture of gears

TEXT When internal residual stresses build up to a point which exceeds the strength of the material, a stress rupture will occur. The internal rupture of a gear is linked to the case core transition interface zone near the top face or the corner of the tooth. Separation of the case/core at the interface can remove the top of the tooth. If the failure is not catastrophic, then the initial defect will initiate a fatigue failure.

Rupture at a case/core interface is generally due to poor manufacturing and materials selection. In addition to this, high service stress levels. In the first case of poor manufacture and materials, failure at the interface could be due to the rapid change in material properties. At the core of a gear the material is required to be tough, whereas at the surface the material is required to be hard. To produce such an effect in ferrous materials different methods of surface hardening are employed. In the majority of cases, gears are hardened by flame or induction hardening. This is where a gas flame or electrical eddy fields heats up the material which is then quenched by air or for faster quenching, water, the idea being to produce a martensitic structure on the surface of a steel gear as martensite is very hard. Martensitic steel is produced by cooling from an austenitic structure (910 degrees C, depending on the carbon content) down to 250°C. The rate of cooling will depend on the material, but to form martensite the rate has to be such that there is little time for the formation of other structures like pearlite. This is shown by the use of Continuous Cooling Transformation curves (CCT) or TTT curves (Time, Temperature, Transformation). These curves are built up of overlapping curves of ferrite, pearlite and bainite transformations of temperature against time to form noses, to which the cooling curve must miss to produce martensite. The problem arises, due to fast cooling, because fast cooling produces a sharp temperature gradient and thus a sharp change in the properties from tough, soft to hard and brittle. It is at this interface that internal rupture can occur. Therefore the solution is to reduce the cooling rate but this might mean that martensite is not formed. A solution to this is to change the position of the

ferrite, pearlite and bainite transformation curves and this can be done by the addition of alloying elements. In steel these elements are to chromium and nickel. The addition of chromium will allow longer cooling times and nickel is used as a grain refiner. This is a very complex area, and will require further investigation, but it is safe to say that non-destructive techniques could find the defect and changes in case-hardening and the specified steel to include chromium and nickel, should reduces this mode of failure. In addition to this a reduction in the service loads will extend the service life.

38 TITLE Stress concentration factors and how to reduce them

TEXT Many failure are caused by stress concentrations. Stress concentrations are changes in section whether that is in thickness, width, or diameter. This stress concentration is greatly affected by the rate of change of section. The rate of change means the change in section shape over a given length. An example of a fast change could be a crack and an example of a slow change could be a ramp, slope, or hump. The effect of such discontinuity or stress raiser is to cause a local concentration in stress. The local concentration of stress can raise the stress level to a level which exceeds the yield strength of the material. Thus a ductile material will plastically deform with the possibility of tearing and a brittle material will involve the separation of a solid accompanied by little or no macroscopic plastic deformation, which could lead on to rapid crack propagation or be the initiation site for a fatigue fracture. The local concentration amplifies the nominal or average stress and this is given by a Stress Concentration factors, Kt. Kt is defined as the maximum localised elastic stress divided by the nominal or average stress, as given in Petersen's book, "Stress Concentration Design" published by John Wiley & Son Inc. The sharper the change in section i.e. a crack the higher the stress concentration. The increase in stress can be over 4 times that of the nominal or average stress. Therefore to help reduce the stress concentration, and the resulting increase in stress it is important to reduce the rate of change in section. This could be achieved by increasing the radius, using a fillet radius with a large radius in place of a sharp corner and, if possible, removing any holes or cut-outs from structural members. Apart from design changes as discussed above, poor manufacturing can lead to stress concentrations, especially when cutting, grinding, or any process that involves the removal or flow of material. The list of processes is massive and it only requires a single defect the size of a dislocation at a grain boundary. In practical terms if the tool is blunt or of poor quality, it will tend to scrape or

score the surface to produces a poor surface finish. This has been seen in many failures in gears with a poor grinding technique and in the production of keyways using too small a fillet radius and a poor surface finish. Surface finishing could reduce the effects of the stress raiser, e.g. shot peening etc, which produces compressive stresses in the surface and good grinding and in some cases, polishing. Good quality grinding and polishing techniques reduce the surface roughness known as the Ra value, and remove any small cracks or other defects and thus reduce the stress concentration effect on the surface of the part. For more information on stress concentration factors and how to reduce them, consider books on "Mechanics of Solids" such as:- "Fatigue Design" by Carl C. Osgood, " Mechanics of Engineering Materials" by Benham & Crawford, etc. Also "Mechanical Engineering's Reference Book" by A. Parrish. All these book will quote from Petersen's book, "Stress Concentration Design" published by John Wiley & Son Inc.

39 TITLE Tooth-bending impact and shear failure of gears

40 TITLE Tooth chipping of gears

TEXT The majority of tooth chipping of gears is due either to tooth to tooth impacts or impact from other objects. Tooth to tooth impact damage is seen as pitting, wear and possible spalling or case crushing, but this is generally seen as wear between gear teeth in which the solution is to replace the gears. If excessive wear has taken place, then standard procedures to reduce wear should be under taken. However, it is important to consider if there was a lack of lubrication or an increase in loading which increased the wear. Some what more serious are impact failure, though not considered to be tooth-to-tooth impact, but from an external force, such as a foreign object. These foreign objects could be object within the gear box or some object that has dropped on the gear, such as a nut or bolt, or a failed tooth from another tooth or gear within the gear box or area. Also the chips could be caused by careless handling before, during and after shipping from the manufacturers, and thus are not considered to be service failures. Tooth chippings appear as random chips, or lumps taken out of the gear, with a general brittle nature, although this depends on the speed of impact and ductility of the gears. Generally failures of this type cannot be repaired and require a replacement gear, but the initial cause must be found so this problem does not occur again. Thus the foreign object has to be found and identified. As stated above this could be a nut, bolt, a chipping from a

tooth, or careless handling. Whatever the cause, this is in a lot of cases very self evident, but care must be taken to make the right decisions.

41 TITLE Remedial action for case crushing failure

TEXT Case crushing will occur when a compressive high load per unit area (stress) is applied to a carburized case on a steel surface and this is typically linked to gear failures. The failure may be seen as small surface cracks and or subsurface defects, which can occur at any time during the service life of the component. The cracks start at the case-core interface and will continue to shear into the core and outward to the surface. For this mode of failure to occur the following four factors must be considered, stress applied at the point of contact, radius of curvature of the contacting surfaces, the thickness of carburized case and the core material hardness. It is important to note that case crushing can be the initiation for a number of fatigue failures and corrosion problems. Also spalling (contact fatigue) of the surface is a major possibility. The difference between case crushing and spalling is that case crushing is generally caused by a impact of two surfaces, where spalling is caused by repetitions of a given stress range. Even though there are differences, the solutions to these problems are similar, so look at the remedial action on "Spalling problems", with details on increasing the core hardness or case hardened depth. Also by redesign, increase the surface area under load (large point of contact area), so to reduce the compressive stresses, whether by impact or repetitive in nature.

42 TITLE Thermal fatigue in gears

TEXT This is linked to the frictional heating found mostly on the rotating faces of gears, that are exerting a high thrust, and also on active profiles of gears. Thermal expansion (heating) and contraction (cooling) initiates a large number of radial cracks and these progress as fatigue cracks into the bore of the gear and along the roots of the teeth. Remedial action associated with this failure is to stabilise the range of temperatures the gear goes through. This is ideally done by reducing the frictional heating effect, as this is detrimental to gears. It is very difficult to suggest methods for reducing the frictional heating effect without fully knowing the system, but generally the sliding speed between the gears has to be reduced, and the contact stresses have to be reduced, i.e. increase the surface area and or decrease the loading.

43 TITLE Galvanic corrosion

TEXT The problem of galvanic corrosion becomes more severe when the metals are far apart in the galvanic series and when the environment is aggressive. It becomes worse when the anode (the part that corrodes) is smaller then the cathode (the protected metal part). To reduce the effect may involve choosing metals close together in the galvanic series, insulating the metals from each other where possible, maintaining coatings from perforation if they are present, reducing the severity of the environment, or providing a third metal as a sacrificial anode.

44 TITLE General corrosion problems

TEXT PRINCIPLES OF CORROSION

Corrosion of metallic and non-metallic materials occurs in unfavourable service environments and generally, part or all of the material is destroyed by means of a chemical or electrochemical action which starts at or near the surface of the material. The term 'corrosion' is usually restricted to metals; however, the chemical attack of acid and alkaline solutions and of the atmosphere upon non-metallic materials, such as concrete and stone, can also be termed as corrosion. The basic cause of the corrosion of metals is their inherent instability in their refined forms. Thus, corrosion can be regarded as the tendency of metals to revert to their more stable chemical forms, such as oxides or sulphates, in which they occur in nature. Corrosion is considered under two general headings; wet corrosion and dry corrosion. Wet corrosion involves liquids, generally associated with water and is so called aqueous corrosion, but it can also take place in a molten metal, molten chemical salt or organic solution environment. Wet or aqueous corrosion is created by a flow of electrons caused by a chemical reaction. This is the electrochemical principle of the battery and requires four components for corrosion to take place, namely, anode, cathode, a conducting solution (the electrolyte) and a metallic connection to complete the circuit between the anode and the cathode.

ELECTRODE POTENTIAL.

The chemical reaction in wet corrosion that produces the flow of electrons, is due to some of the metallic atoms losing their valence electrons while passing into the aqueous solution as metal ions, this is called the oxidation reaction. The reaction involved can be represented in the following form:- $M <---> Mn^{++} + ne^-$ Where M represents the metal atoms, Mn^+ the metal ions, and ne^- the valence electrons of the metal involved. Solution equilibrium is achieved after a short time, because the rate of ion formation is equalled by the rate at which the ions already in solution recombine with elections to form metal atoms. The production of metal ions and electrons causes the build up of an electrical potential on the metal electrode. This is known as the electrode potential and its value depends upon the chemical activity of the metal itself and the type of solution in which it is immersed. Since all metals do not oxidise (i.e. lose electrons) with equal ease, the value of the electrode potential for any given metal provides some indication of its tendency to corrode in any given solution. As the electrode potential of a metal is difficult to measure, the difference in potential is measured between a given metal and a standard hydrogen electrode at 25 °C in a molar solution of their ions. A standard Hydrogen electrode is given an arbitrarily value of zero.

THE ELECTROCHEMICAL SERIES

When metals are arranged in order of the standard electrode potentials, an electrochemical series of metals results, as shown below, Standard electrode potential Eo volts at 25°C

$Mg = Mg^{++} + 2e^-$	+2.34
$Mn = Mn^{++} + 2e^-$	+1.05
$Cr = Cr^{3+} + 3e^-$	+0.71
$Fe = Fe^{++} + 2e^-$	+0.440
$Co = Co^{++} + 2e^-$	+0.277
$Ni = Ni^{++} + 2e^-$	+0.250
$½H_2 = H^+ + e^-$	+0.000

GALVANIC CELL

A useful way to understand wet or aqueous corrosion is through a model known as the Galvanic cell model, The arrangement is of a metal electrode with a high electrode potential, such as iron (mild steel) which becomes the anode. This is externally connected to another metal electrode having a lower electrode potential, which becomes the cathode, and both electrodes are placed in a tank of water which acts as an electrolyte. The model works due to the iron electrode having a higher electrical potential, which becomes the anode and thus the metal forms positive ions which pass into solution in the reaction:-

$$Fe \rightarrow Fe^{2+} + 2e^{-}.$$

Thus, there is a surplus of electrons at the anode which flow through the wire to the cathode. Since there is now a surplus of electrons at the cathode, there is no tendency for the cathodic metal to go into solution. Therefore, the metal with higher electrode potential becomes the anode, is oxidised to its ions, and is thus corroded, while the metal with the lower electrode potential becomes the cathode and is protected from corrosion. Hydrogen gas is evolved from the cathode, since the hydrogen ions are produced by the reaction:-

$$H_2O \leftrightarrow H^{+} + (OH)^{-}$$

The ions take up surplus electrons at the cathode and form gaseous hydrogen by the reaction:-

$$2H^{+} + 2e^{-} \rightarrow H_2$$

Since there are relatively few H^{+} ions available from the dissociation of the water electrolyte, the cell reaction proceeds very slowly. However, if the water is acidified, the concentration of H^{+} ions is increased and the cell reaction and the corrosion of the anode is more rapid. With the dissociation of the water and the removal of the H^{+} ions, there is a surplus of $(OH)^{-}$ ions at the cathode. Any Fe^{3+} ions present will migrate to the cathode and combine with the $(OH)^{-}$ ions, to form ferric hydroxide, or hard rust which is insoluble. Either forms on the cathode or falls to the bottom of the tank.

$$Fe^{3+} + 3(OH)- \rightarrow Fe(OH)^{3}$$

The presence of oxygen in the electrolyte is extremely important as it increases the rate of corrosion. Firstly by oxidising the Fe^{2+} ions to increase the concentration of Fe^{3+} ions and secondly by increasing the number of $(OH)^{-}$ ions present according to the reaction below, additionally there is also an oxygen reduction reaction:-

$$H_2O + \tfrac{1}{2}O_2 + 2e^{-} \rightarrow 2(OH)^{-}$$

In summary, the following factors increase the rate of corrosion of the anode:-

1. A large difference in the electrode potential between anode and cathode.

2. Increased acidity of the electrolyte.
3. Increased oxygen concentration in the electrolyte, particularly around the cathode.

TYPES OF GALVANIC CELL. Galvanic cells can be classified into three broad categories:-

1. Concentration cells.
2. Composition cells.
3. Stress cells.

Concentration cell corrosion occurs where a single piece of metal is exposed to varying concentrations of electrolyte and other factors important to corrosion such as oxygen concentration, which is known as differential aeration. Corrosion is greatest, where there is the least oxygen. Composition cells may occur between any two dissimilar metals or where dissimilar phases in a single metal are in contact. The phases or metal having the higher electrode potential become the anode, and corrode in favour of the other phases or metal in contact which becomes the cathode. An example of this is that quenched steels corrode more slowly than quenched and tempered steels, because of the absence of a precipitated phase (carbide) in the fully martensitic steel. Many corrosion microcells can be set up between the areas of differing phases. Stress cell are evident in cold worked metals, where areas of higher stress become the anode. For example, a bent body panel, the edge becomes the anode and the unstressed areas become the cathode. Also, stress cells are found at grain boundaries in a pure metal; they become anodic since the atoms at the grain boundaries are not in the regular crystal lattice and are therefore stressed, that is, at higher energy levels then other atoms present.

PASSIVITY OF METALS, The formation of films.

A metal or alloy is said to exhibit passivity if it has a much higher corrosion resistance than its position in the electrochemical series would indicate is normal. Examples of these passive metals are titanium, chromium, aluminium and stainless steel; each of these metal alloys exhibits good corrosion resistance in oxidising atmospheres but become chemically active in reducing atmospheres. As a result, stainless steels are used with oxidising agents or where oxygen is present, such as nitric acid or outdoor environments. Stainless steels are particularly susceptible to attack by chlorides, such as in hydrochloric acid or sea water. In the latter medium however, pitting only occurs at low flow rates (0.1m/s). At flow rates

greater than 2m/s, corrosion occurs uniformly but slowly (25µm/y). In stainless steel type 316, molybdenum additions help reduce pitting in some environments. There are two alternative theories, which have been proposed to account for passivity. One theory proposes the formation of a very thin layer of insoluble, nonporous, self- healing oxide film which acts as a highly protective surface layer (ref 1, 2, 3, 4). The alternative theory assumes the presence of a surface layer of chemically absorbed oxygen molecules (one molecule thick) which provides the surface protection.(ref 1, 4) Whichever theory is preferred, the effect of the surface layer is to reduce the corrosion of the metal and make the anode more noble (or cathodic). If, however, the passive film is ruptured and is prevented from repairing itself, corrosion of the steel will continue, and will result in either pitting or a general attack over the whole surface of the steel, depending on whether the rest of the oxide film remains intact or whether it is progressively removed from the steel surface. The self-healing properties and the speed of film formation of high chromium steel were researched by Forrest, Roetheli, and Brown (ref. 5). They measured the rate at which oxygen was absorbed by the metallic (i.e. oxide free) surfaces of ordinary carbon steel, 14% chromium steel, and "18-8" chromium-nickel steel. They showed that for a period of thirty or forty seconds all three metals absorbed oxygen at the same rate, but then absorption rapidly fell off and became negligible with the two stainless steels. It continued at an undiminished speed for the carbon steel during the whole period of the experiment (about ten minutes). If this could be visualised it would be seen as an absorbed layer of (CrO4) 2- ions responsible for the passivation of chromium-based stainless steels in an oxidising atmosphere on or near the surface of stainless steel.

Ref:-

1 Schlenker, B.R.,"Introduction to Materials Science" SI Edition, John Wiley and Son, 1981.

2 Monypenny, J.H.G.,"Stainless Iron and Steel" Vol. 1, Chapman and Hall Ltd, 1951.

3 Perry, B.,"Corrosion Principles for Engineering Technicians", Department of Industry, 1982.

4 Ray, Martyn S.,"The Technology and Applications of Engineering Materials", Prentice Hall International.1987.

5 Kirkby, H.W. and C. Sykes, "Properties of Materials Intended for Gas Turbines", Symposium on High temperature steels and alloys for Gas Turbines, Iron Steel Inst. Rept.43, 1952.

45 TITLE Crevice corrosion

TEXT Crevice corrosion is a form of localised attack that most often occurs in narrow fissures, bolted and lock tight joints, junctions, cracks, poor quality welds or under deposits, especially where oxygen access is poor and a stagnant electrolyte solution is present at metal to metal or metal to non-metal junctions allowing concentrations of corrosive species, particularly chloride ions to be generated within a crevice or stagnant area. This promotes rapid localized attack in crevices, with a minimal attack seen on the surfaces.

The solutions are either by proper alloy selection and/or the adoption of a number of practical procedures to avoid the possibility of crevices or stagnant areas occurring by either redesigning in order to use a different fabrication method, i.e. welding instead of bolting, making sure all deposits are flushed out; design out cracks and crevices, etc. If welding is to be used instead of bolting then make sure the weld profile is smooth and without cracks and crevices which can so easily be formed during welding, because the crack could lead to corrosion and fatigue and corrosion fatigue, stress corrosion, etc. (See other cases) Crevice corrosion can occur in normally passive metals, such as stainless steel, titanium (Ti) and aluminium (Al). Many stainless steels contain Ti to improve weldability (types 321, 316Ti, and 430Ti). Cold working and a corrosive environments can initiate corrosion at microcrevices created when the brittle intermetallic titanium carbonitrite particles fracture. Microgalvanic effects between the steel and the Ti will enhance the effect. Ti can be attacked by halides, chlorine, chlorine dioxide, and hypochlorite solutions at elevated temperatures (90°C). Al can be attacked when combined with an unfavourable dissimilar metal in hostile environments. For example 3 years exposure to sea air for Al-Mn (AA 3003) cladding to a steel frame by 304 stainless steel fasteners caused crevice corrosion.

Reference; Betts, A.J.; Boulton, L.H.; "Crevice corrosion: review of mechanisms, modelling, and mitigation" British Corrosion Journal, (1993) Vol. 28, No.4, pp279-95. (includes 104 other references to crevice corrosion)

46 TITLE Pitting corrosion

TEXT SELECTIVE CORROSION OR PITTING

Pitting corrosion is similar to crevice corrosion but localized around small pits or cavities on a metal surface due to differences in oxygen and ion concentrations at the base of pits which becomes anodic, compared to the surrounding metal to which atmospheric oxygen can diffuse. Pits are commonly the results of the presence of chloride compounds (sea salt), especially near coastal regions or sulphur compounds near industrial areas. Solid particles help to form a fog which produces concentration cells when deposited on the metal. The washing effects of rain will reduce the effect by removing such dirt and other corrosion products. Pitting is due to an autocatalytic electrochemical process, that is when a compound reaches a critical humidity level which depends on the compound and the metal, the initiation of pits can occur which are dependent on local concentration variations of the corrosive compound on the surface. The pits generally grow downwards, (though this is unstable in the first stages) as they retain the concentrated solution within them. The metal ions formed at the bottom of the cavity migrate upwards and react with the hydroxide ions to form hydroxide of the metal at the mouth of the crevice. The position of the corrosion product at the mouth, accentuates the corrosion by making the diffusion of oxygen to the anode more difficult, and if the cathodic area is large severe pitting may occur. Foreign matter such as sand in condenser tubes causes this type of failure.

PITTING CORROSION IN BRASS The pitting of brass condenser tubes sometimes occurs due to dezincification. This consists in the solution of the brass following by the precipitation of copper by zinc in the brass; the net result is the selective removal of zinc. A red copper deposit, underneath a white layer, is usually seen near the perforation. It is now practice to add arsenic to brass to minimise this trouble at low water velocities. A localized attack frequently occurs near the inlet ends of condenser tubes, due to impingement attack of air bubbles which carry away the corrosion products. Under such an attack copper has poor resistance, this can be improved by the addition of nickel (10-30%) and iron (1-2%). Quenching from 900 C is desirable to disperse the iron. The collapse of vapour bubbles on ship propellers and pumps can cause an attack known as "Cavitation Erosion"

PITTING CORROSION IN STEEL When a series of conditions forces the passivity (protective oxide film) to disappear from some point on the surface of a stainless steel component, this area transforms into the anode of a galvanic corrosion cell, which corrodes at the anode under the galvanic action of differing electro-potentials between area with oxide films and ones without oxide films. Generally, corrosion first appears by very fine pitting, which rapidly develops in both depth and length. A typical case of this corrosion type is that produced by sea water in almost all types of steel and because it is so difficult to detect, this makes it potentially dangerous. It is the chlorides, bromides and hypo-chlorides which present the greatest aggression towards the protective oxide film. Also, if dirt accumulates on the surface of the stainless steel, the access to oxygen is stopped on the dirt covered areas, thus, a protective oxide layer cannot reform after an attack. This then forms a galvanic action between the clean and dirty areas. As with many other types of corrosion, it is the composition and structure of the steel that are factors which greatly influence this type of corrosion. Austenitic stainless steels containing molybdenum show good resistance to this corrosion. This can be improved with the addition of copper and nitrogen which reduces the tendency towards corrosion by pitting.

47 TITLE Intergranular Corrosion

TEXT INTERGRANULAR CORROSION.

Intergranular corrosion in stainless steel can be a problem if the carbon content exceeds several tenths of a percent. However in recent years this problem has been reduced by the introduction of tighter production control. In the as-received condition the stainless steel has carbon in solution in the austenitic (f.c.c.) lattice. It is usually in a single phase austenitic structure. When the metal is exposed at temperatures in the range of 400-900 °C (1000-1500 °F) during operations such as welding and cutting by heat sources such as gas cutting, plasma cutting, electric arc welding, the carbide $Cr_{23}C_6$ precipitates. Since precipitates are often nucleated in disoriented regions of the crystal lattice, grain boundaries are the usual locations of carbides, unless cold working has provided dislocation sites within the grains. Because of the high chromium content of the carbides, the nearby regions are impoverished in chromium in the process of forming the carbides. The chromium level can fall to below 10% in these regions around the grain boundaries. Hence, these regions become less passive when compared with the surrounding matrix. This results in a galvanic action between the grain

boundary regions and the higher chromium content regions within the grain. Thus the low chromium-iron matrix (the anode), becomes corroded and leaves the chromium carbides, (the cathode), which if recovered after corrosion and examined under the electron microscope appear as plate like crystals. The risk of this type of corrosion can be reduced by using a solution heat treatment at 1093 °C (2000 °F)followed by a rapid quench after the initial heating process. Another solution to this problem, is to change the composition of the material. The most obvious is to reduce the carbon content to a safe level (0.03% by weight) so that there is insufficient carbon to form carbides to develop galvanic action in grains. An alternative approach has been by the addition of one or a combination of titanium, niobium (columbium), or tantalum in amount sufficient to react completely with the carbon in the melt to form carbides of the following respectively, TiC, NbC, TaC, which are more stable in steel than is chromium carbide. It has been found that these added elements increase the mechanical properties, notably the creep resistance at all temperatures. This is due to the precipitation of carbides near dislocations. (Kirkby, H.W. and Sykes, C., (1952) "Properties of materials intended for gas turbines", Iron and Steel Institute, Spec. Report 43.)

48 TITLE Caustic Cracking

49 TITLE Caustic cracking due to poor rivetted seams in a steel ships boiler

TEXT Repair the boiler to remove the crack and crevices by either high quality rivetted seams or welded seams. In most cases it is best to weld. Finally treat the feed water to maintain the ratio of sodium sulphate to caustic soda to British Standard 1170. ref:- British Engine Boiler & Electrical Insurance Co. Ltd, Technical report March 1962, Vol IV, pp50-53

50 TITLE Brittle fracture of a rail arising from flame-cutting

TEXT If a rail has to be cut in any form then try not to use sharp changes i.e. corners, etc. Follow the rules for keeping the stress concentration to a minimum when you design the shape of your cut. Try not to use a heating/melting process to cut the rails, i.e. flame cutting, try a machining process, though this would be difficult on site. If flame cutting is to be used then remember to cool the surface and the surrounding area slowly so you don't form martensite. The process of flame cutting is similar to welding so follow all the precautions

you would do if you were welding. ref:- British Engine Boiler & Electrical Insurance Co. Ltd, Technical report March 1962, Vol IV, pp68-69

51 TITLE Fatigue fracture due to abrupt thread run-out

TEXT This type of failure need not occur if the design had been better; it could have been improved in several way. For instance, the shank threads should have been run out gradually over a distance equal to the shank diameter or, alternatively, the shanks should have been reduced in diameter to slightly less then that of the thread root for a similar distance. In reducing the diameter, make sure that it can still stand the fatigue loading cycle, it is better to increase the diameter of the shank's thread and nut so that the root is equal or greater than the shank itself. The bending stresses could also be greatly reduced by the introduction of hardened steel hemispherical washers under the shank nuts. ref:- British Engine Boiler & Electrical Insurance Co. Ltd, Technical report March 1962, Vol IV, pp60-61

52 TITLE Delamination & longitudinal split in extruded aluminium alloy mast

TEXT BS 1474 6061 Aluminium alloy mast delaminated and split longitudinally due to poor extrusion, seen as extremely coarse grains resulting from too slow cooling rate. Also dross, piping defects, and back-end defects lead to delamination and areas of high friction - poor flow, produce oxide accumulation thus lead to poor welded joints, thus longitudinal splits EM/1547/90

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53 TITLE Strain-age Embrittlement

54 TITLE Stainless Steel Engineering Guide (Nickel development Institute)

Browse Graphic ToolBook : run Page: c:\cbrx13dk\nidi\go.exe

55 TITLE Crevice Corrosion Engineering Guide (Nickel development Institute)

Browse Graphic ToolBook : run Page: c:\cbrx13dk\guide\tmodel.exe

56 TITLE Abrasive water jet cutting, What is it & how it can help

Browse Graphic ToolBook : run Page: c:\cbrx13dk\enghype\h2ojet.tbk

57 TITLE Electro-Discharge & Electro-Chemical Machining, its uses.

Browse Graphic ToolBook : run Page: c:\cbr13xdk\enghype\electr.tbk

58 TITLE Corrosion Fatigue of overlay welded shaft on a ferry stabiliser fin

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59 TITLE Hydrogen-Damage failures

TEXT Metals Handbook, 9th Ed., Vol 11, Failure Analysis and Prevention, American Society for Metals, p245-251, 1986

60 TITLE Dezincification and denicklification

TEXT Dezincification is a selective leaching process in brass, whereby zinc dissolves and a brittle low strength spongy porous copper deposit remains. (being the more noble element) Hence for Copper-nickel alloys, nickel is leached out, termed "Denickelification". Dezincification can occur after exposure to fresh or sea water and in components for boats, shipping, etc and in heat exchangers. The selective leaching of brass can be detected visually by the reddish copper-coloured appearance of the copper deposits that come in layers or plugs of material.

The two forms of Dezincification plugs and layers can be identified by the fact that plug type dezincification spreads out less on the surface than layer type dezincification. An acidic environment favours layer type attack.

The mechanism is that the brass dissolves slightly, then the copper ions are displaced by more zinc or nickel going into solution, and the copper plates out. On closer metalographic inspection, different layers can be seen and this relates to the differential electron corrosion potentials of the different phases. Brass is made up of Beta (47% Zn, -0.285 eV) and Alpha phase (<38% Zn, -0.230 eV). The beta phase is preferentially attack first which makes the brass porous with unaffected alpha phase. Then both Alpha and beta are attacked to produced a porous copper outer layer.

Dezincification is accelerated by waters having a high content of oxygen, carbon dioxide, and chloride (chlorination); and by elevated temperatures and low water velocities.

To avoid the problem of Dezincification a change in material is required in that the zinc content of the component should be lowered, ideally to around 15%. The most sensitive alloys contain 40% zinc and have a second phase (beta) which aggravates the problem. In severe cases, where the 30% zinc is troublesome, the addition of tin and arsenic (1% Sn, 0.04% As) and antimony or reduction of the zinc to below 20% will alleviate the problem. Also if cost is not a major factor, a Copper-nickel alloy is best, although this is prone to denickelification, it will take a lot longer than Dezincification of brass. Also avoid environments where the solution becomes stagnant and deposits can accumulate on the metal surface. (Baboian, R. (Robert), (1981),"Automotive corrosion by deicing salts", NACE Corrosion/80 meeting, Chicago, USA, March 3-7, 1980, page 273)

Browse Graphic ToolBook : dezinc2

61 TITLE Impeller failure due to a repair or built up weld with pores

Browse Graphic ToolBook : : seacat1 PAGE : c:\cbrx13dk

62 TITLE Microbiological Corrosion

TEXT Bio-Fouling and Bacterial corrosion in marine, oil fields, aluminum jet fuel cells, and sewage pipe environments are caused by anaerobic & aerobic bacteria, fungus, and macro-organisms (barnacles, mussels, etc) change air, oxygen, and ph levels to acid, through deduction or oxidation of sulphur compounds and the suppression of a cathodic protective response .When several of the below are observed, it can be assumed that microbiological corrosion has occurred.

1. Pitting corrosion rather that lateral types
2. Presence of microbial slime masses
3. Hydrogen sulfide in anaerobic systems
4. Ferric (ous) hydroxide in anaerobic systems
5. Large bacterial populations

6. Either an aqueous system or a non aqueous system that allows the accumulation of water in some areas. This generally means flows at or below 0.5 m/s, though there are many exceptions.
7. Temperature below 65°C at some intervals and below 125°C at all times.
8. pH is not a reliable indicator but most microbiological corrosion occurs in the pH range of 4.0 to 9.0. There are numerous exceptions.

Reference

Lutey, Richard."Microbiological Corrosion" The International Corrosion Forum, National Association of Corrosion Engineers, Paper 39, March 3-7, 1980, Palmer House, Chicago, IL, USA.

63 TITLE Ductile failures

TEXT Ductile fracture

Flat-face tensile fracture, in ductile materials are produced by triaxial tensile stress systems that corresponds to a plane strain condition in the case of a thick plate. Necking precedes fracture, and the plane of the flat face fracture is normal to the direction of the largest tensile stress. The flat face fracture is terminated by a shear lip that extends to the free surface. and the ration of area of the flat face fracture to shear lip usually increases with section thickness. Microscopic examination at 100X or greater will reveal equiaxed dimples that are formed by microvoid coalescence.

Shear-face tensile fracture, in ductile materials are produced under plane stress conditions (that is, in thin walled sections or near free surfaces) with or without necking, and typically occurs at angles of about 45 ° to the surface of the part. Examination in steel would reveal a 45 ° fracture surface and a fine gray, silky appearance. Necking would be faintly visible in threaded areas if part was a bolt. Microscopic examination of shear faces tensile fractures as well as the shear lips of flat face tensile fractures in ductile materials at magnifications of about 100X and greater reveals elongated dimples with their long axis in the direction of the shear force. The elongated dimples produced by tensile shearing point in the opposite directions on the mating fracture surfaces. Elongated dimples are also produced by tensile

tearing, but such dimples point in the same direction on the mating fractures surfaces which distinguishes them from shear dimples.

64 TITLE Neutron Embrittlement

TEXT Neutron embrittlement. Irradiation of Low-alloy steel could cause large increase in ductile to brittle transition temperature and be subjected to an intergranular failure. Mostly occur in body cantered cubic structures (non-austenitic steel) at low temperatures. X-ray, gamma, heavy-particle radiation or fission fragments in nuclear fuel also alter material properties

During neutron irradiation the transition temperature may be substantially increased, depending on such factors as the neutron dose, neutron spectrum irradiation temperature, and steel composition. The amount by which the transition temperature increases because of neutron irradiation is usually at least 17 °C (30 of) but less than 200 °C (360 of).

High-strength steels, which have lower initial nil-ductility transition temperatures than low-strength steels, are generally less susceptible to radiation embrittlement. Steels with low initial nil-ductility transition temperatures, fine-grain microstructures, and high dislocation densities generally offer greater resistance to neutron embrittlement. Neutron embrittlement renders the steel more susceptible to intergranular fracture. Heat-treatment practice greatly affects the susceptibility of a steel to neutron embrittlement. Steels with tempered-rnartensite microstructures are less susceptible than those with tempered upper bainite or ferritic microstructures. Vacuum degassing and control of such elements as copper and phosphorus help reduce susceptibility to neutron embrittlement.

Ref: Metals Handbook Vol. 11, 9th Ed., Failure Analysis and Prevention, 1986, pp100.

65 TITLE Fretting Fatigue

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66 TITLE Buckling failures

TEXT Buckling occurs when a critical combination of in compressive magnitude and or a point of load is applied in compression to a beam, post, column, or any member which causes deflection to suddenly increase in a non-linear manner resulting in damaged which generally looks ductile. The columns, beams, etc are generally smaller in cross section than in length.
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67 TITLE Brinnelling Failure

TEXT When the static force or load between two curved surfaces in contact results in local permanent plastic yielding. A ball bearing race can become brinnelled leading to increased vibration, noise, and heating.
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69 TITLE Use a 600-series nickel-base superalloy

70 TITLE Eliminate residual magnetism

71 TITLE Impact failure induced by water hammer on a welded pipe

TEXT Remedial actions to avoid impact failure induced by water hammer on a welded pipe :
- Reduce residual welding stresses.
- Improve the impact toughness of the steel by producing a more uniform microstructure.
- Reduce the water hammer.

Chapter 11 Semantics in failure analysis and the development of rules.

11.0 Introduction

CBR Express utilises a natural language interface to collect a description of the current search case without the need for any special syntax or formatting. Matching is undertaken between the search case and cases in the database through a similarly of words used in the description. Hence the words used in the two descriptions are important for successful matching.

This chapter discusses how the matching of cases can be made more effective by analysing the types of words used. This allows certain common words to be excluded and hence matching then involves words which have specific meanings.

11.1 Semantics

Many different languages could be used within this and other expert systems. English was considered the most appropriate, because it is the most widely used language within both the computing industry and academia. Additionally, there are many language translators available to translate English to either German, Spanish, french Italian or Portuguese (Language Assistant and Power Translator by Globalink,(http://www.globalink.com). These could help by either translating the expert systems output or producing different language versions of the expert system. With the recent developments in the World Wide Web as discussed in Chapter 14, using an on-line language translator is now possible (http://www.infospace.com). This opens up the possibilities of using this or any other expert system in a different language to that which was used to develop it.

One of the problems with English, which has an extremely extensive vocabulary, is that there are many words which express the same idea, and conversely identical phenomena or concepts can be expressed by different words. In addition, American English has some slightly different spellings of some words than British English, e.g. analyze - American; analyse - British.

This semantic problem, is further complicated by the fact that as failure analysis is a technical subject it has its own terminology. Standardising terminology is important in an expert and knowledge based system. This helps both the searching criteria and the user's general

understanding of the system. However, when the standard terminology of failure analysis was investigated, it is was found, that as in normal English there were many situations where either one word had many meanings or one meaning had several words to denote it.

For example:- What is the difference between the following?

I. Flaw or defect:- A defect is an unacceptable flaw.

ii. Fracture or rupture:- A rupture has to include some plastic deformation, fractures do not.

Each meaning is used interchangeably with the other. This complicates failure analysis as if the technically incorrect word is used as an input the expert system will arrive at a solution which to it is correct, but is actually incorrect, e.g. ***the component ruptured*** might mean the component fractured after plastic deformation (technically correct) or the component fractured (no reference to whether plastic deformation occurred or not - technically incorrect use of the word ruptured). This greatly complicates failure analysis using an expert system based on a natural language input to describe the failure. To alleviate this problem, wherever possible, both words were included in the case description. However as the number of cases increases, the problem increases and several combinations of words have, wherever appropriate, been included in the case description.

11.1.1 Excluded words

The main advantage of using a natural language interface is both to reduce the number of questions the user is asked and to allow free expression in detailing the problem, rather than to be drawn down one line of thought, as would be typically done in a rule based system. However, problems of spelling, grammatical and standard term errors could still occur. To reduce this problem, a structured understanding of the possible words used in the expert system was undertaken to analyse which words could be excluded from the search routines. This was done by examining all the words within the case base descriptions in the expert system. At the time this analysis was undertaken there were 49981 words. As many failure histories cases used in the expert system came from different sources, analysis of these words would show common words used in failure analysis. A list of the most frequently used word in the expert system is given below. The list has been produced from using Grammatik 5

which is able to list word usage. The word usage list is extremely long covering over 50083 words and thus not all words are included. Additionally, words required for programming the expert system, for example:- answer, default, scoring, are excluded. The list is given in numerical order down to 98. The numbers are the total number of occurrences of that word in the expert system.

2483, the
1147, is
1065, a
865, or
821, to
809, in
781, of
688, and
593, failure
558, yes
491, surface
490, stress
452, component
430, any
399, there
380, your
331, has
284, fracture
273, by
259, does
256, metal/s
249, fatigue
246, be
241, corrosion
229, at
217, brittle
210, high
194, it
189, begin
188, end
179, other
177, if
174, occurred
169, can
166, have
161, for
159, around
157, was
152, primary
152, with
150, you
149, into
148, steel
146, metal
140, from
140, on
140, secondary
139, before
139, environment
139, would
138, as
135, level
131, strength
129, consider
122, damage
112, temperature
110, metals
109, occur
108, process
108, low
107, liquid
106, like
105, water
103, group
102, room
99, used
98, load

In examining the list above, there are some words which are extremely common. Some of these words (those words underlined) should be excluded from the initial matching search between the entered description and the stored descriptions in the case base as they can cause too many unrelated links to case histories.

Other words such as homonyms, or other similar or split words, can also be removed from the searching mechanism. This is because these words could be written incorrectly by either the user in the search description or the author in the case base, and because these words are not ideal engineering keywords, thus of little help in the searching routes.

Therefore words have been excluded because either they did not aid diagnosis or they could be detrimental to any search. The excluded words can be described as words that are:-

Commonly confused and abused words

Similar words

Homonym

Filler words; Articles, Pronouns, Conjunctions, Preposition, and interjections

This makes an extremely extensive list of words some of which are detailed in section 11.2. However stating that the included words are those which have a visual meaning would be simpler.

11.1.2 Commonly confused words

Commonly confused words are words that can confuse a writer because their sounds, spellings, or meanings are similar: Generally a writer cannot tell if a similar word would be a better choice or not. Usually, this is because the two words have the same part of speech (for example, "acid" and "acrid").

11.1.3 Homonyms

A homonym is one of two or more words that have the same pronunciation and often the same spelling but differs in meaning (Reader's Digest, pp739). They often present the most difficulty in English language and grammar and are ideal candidates for exclusion. Also their actual meaning does not add or represent any tangible (visible) object. For example nut, bolt,

shear fracture have a visible meaning whereas, "it's, their, they're, where," have no visible meaning. When describing if a word has a visible meaning, it must be taken in the broadest sense, i.e. air is visible in a balloon or bubbling through water. When words have no visible or tangible meanings then they make poor keywords. Some of the most frequently confused homonyms are as follows,

it's = contraction of "it is"

its = possessive form of "it"

their = possessive form of "they"

there = refers to a place

they're = contraction of "they are"

threw = past tense of "throw"

through = passing in and out of something; done with

to = preposition (to the store) or infinitive (to laugh)

too = means "also" or "overly"

two = the number "2"

who's = contraction of "who is" or "who has"

whose = possessive form of "who_"

11.1.4 Similar Words

Similar words are words sometimes mistaken or mistyped for other words, usually due to similar spellings and sounds. Words that look alike may have the same letters in common, only arranged slightly differently. Mistyped words are more difficult to correct as this relies on the users' ability. However, many commonly mistaken words are mistyped or misspelled, thus, by excluding these words, mistyped words can in theory be controlled. The following is a very partial list of the most frequently confused words, which should be excluded from the matching search.

closest/closet	form/from	past/passed	
personal/personnel	quiet/quite	than/then	united/untied

11.1.5 Filler words

Filler words are any word used to aid the readers understanding of a sentence. However they make poor keywords, because these words do not have a visible meaning. The filler words can be grouped as follows:

Filler word	Description	Examples
Articles,	The words that normally start a sentence	a, an, the
Pronouns	A word that replaces a noun	any(thing), each, (n)either, he, her(self) , him(self), I, it(self), mine, me, my(self), oneself our(selves), she, some(body/one/thing) that, their(s/selves), them(selves), these, they, this, those, us, what(ever), which(ever), who(ever), whom(ever), whose, you, your(s/self/selves),
Conjunctions	Linking words, phases, or clauses like And	after, although, and, as, as if, as though, because, before, both, but, either, even if, even though, how, however, if, in order that, lest, only, or, nor, neither, since, so that, that, the minute, unless, until, when, whenever, where, whether, while
Preposition	to express relationship such as time, place, possession, etc	after, about, above, across, against, among, amongst, around, at, before, by, due during, except, for, from, in, into of, on, opposite, outside, over, owing to, since, till, to, towards, under, until, upon, with.
Interjections	An exclamation.	hi, oh, hey

(Ref: Harrap's English Grammar 1989)

11.2 List of Excluded Words.

The following word list are words which should be excluded from the searching algorithm. They are combination of all the sources in section 11.1 and words which are suggested by CBR-Express for exclusion indicated by underline. Words in bold are common words in the expert system.

A
ABOUT
ACTION
ACTIONS
ADVICE
ADVISE
AFFECT
AFTER
AGAIN
AGAINST
ALL
ALLUSION
ALMOST
ALONG
ALRIGHT
ALSO
ALTERNATE
ALTERNATIVE
ALTHOUGH
ALWAYS
AM
AMONG
AMONGST
AN
AND
ANSWER
ANOTHER
ANTE
ANTI
ANY
ANYHOW
ANYMORE
ANYTHING
ANYWAY
ARE
AROUND
AS
ASSURE
AT
AWAY
BACK
BE
BECAUSE
BECAME
BECOME
BECOMING
BECOMES
BEEN
BEFORE
BEGIN
BEING
BETWEEN
BOTH
BROWSE
BUT
BUY
BY
CAME
CAN
CANNOT
CASE
CASES
CHANGE
CHANGES
COME
COMES
COMING
COMPLEMENT
COMPLIMENT
CONTINUAL
CONTINUOUS
COULD
CLOSEST
CLOSET
CREATION
DAY
DEPENDANT
DEPENDENT
DID
DIDN'T
DIFFERENT
DISCREET
DISCRETE
DISINTERESTED
DO
DOES
DOESN'T
DOING
DONE
DON'T
DOESN'T
DOWN
DUE
DURING
EACH
ECONOMIC

ECONOMICAL
ED
EFFECT
EITHER
ELSE
EMINENT
END
ENSURE
ETC
EVEN
EVER
EVERY
EVERYTHING
EVERYONE
EXCEPT
FATHER
FARTHER
FEWER
FIRSTLY
FOR
FORM
FROM
FRONT
FULL
FURTHER
GET
GETS
GETTING
GETUP
GO
GOES
GOING
GONE
GOT
GOTTEN
GOTO
GROUP
HAD
HANDBOOK
HAS
HAVE
HAVING
HE
HE'S
HER
HERS
HERE
HERSELF
HEY
HI
HIM
HIMSELF
HIS
HOPEFULLY
HOW
HOWEVER
I
I.E.
IF
ILL
ILLUSION
I'M
IMMINENT
IMPLY
IN
INFER
ISN'T
INSURE
INTO
IS
IT
ITS
IT'S
ITSELF
JUST
KNIGHT
LAST
LAY
LEAVE
LEAVES
LEAVING
LEFT
LEAST
LEST
LESS
LET
LETS
LET'S
LETTING
LEVEL
LIE
LIKE
LIKED
LIKES
LIKING
LOOSE

LOSE
MADE
MAKE
MAKES
MAKING
MANY
MAY
MAYBE
ME
MEANTIME
MEANWHILE
MIGHT
MINE
MINUTE
MORE
MOST
MUCH
MUST
MY
MYSELF
NEITHER
NEVER
NIGHT
NITE
NO
NONE
NOR
NOT
NOW
OCCUR
OCCURRENCE
OCCURRENCES
OCCURANCE
OCCUPANCE
OCCURANCES
OCCURRED
OCCURRENCE
OCCURRED
OCCURRING
OCCURS
OH
OF
OFF
ON
ONLY
ONTO
OPPOSITE
OR
ORDER
OTHER
OTHERS
OTHERWISE
OUR
OURS
OUT
OUTSIDE
OVER
OWING
PERSONAL
PERSONNEL
PRACTICE
PRACTISE
PREDOMINANT
PREDOMINATE
PRINCIPAL
PRINCIPLE
PROGRAM
PROGRAMME
PUT
PUTS
PUTTING
QUESTION
QUESTIONS
QUIET
QUITE
RAN
RUN
RUNNING
RUNS
SAID
SAME
SCORING
SECONDLY
SEE
SEEN
SEES
SHALL
SHE
SHE'S
SHOULD
SINCE
SO
SOME
SOMEBODY
SOMEONE
SOMETHING

SOON
STANDING
STATIONARY
STATIONERY
STILL
STOOD
SUCH
SURE
TAKE
TAKEN
TAKES
TAKING
TEXT
THAN
THAT
THAT'S
THE
THEIR
THEIRS
THEM
THEN
THERE
THERE'S
THESE
THEY
THEY'RE
THIS
THOSE
THOUGH
THREW
THROUGH
THUS
TO
TOO
TOOK
UNDER
UNLESS
UNINTERESTED
UNITED
UNTIED
UNTIL
UP
UPON
UPTO
UP TO
UPTON
USUALLY
VERY
VOL
WAS
WAY
WE
WEATHER
WELL
WENT
WERE
WE'RE
WHAT
WHATEVER
WHEN
WHENEVER
WHERE
WHERE'S
WHETHER
WHICH
WHICHEVER
WHILE
WHO
WHOEVER
WHO'S
WHOM
WHOSE
WHY
WITH
WITHIN
WITHOUT
WILL
WON'T
WOULD
YES
YET
YOU
YOU'RE
YOUR
YOURS
YOURSELF
YOURSELVES

The words listed above are only an indication detailing some of the words which should be excluded from the expert system. A detailed analysis (section 11.1) of any standard English dictionary would provide an even more extensive list of words which could be excluded.

11.3 The development of rules

During this project, it was found that the development of an effective failure analysis expert system based solely on rules or past case histories, would entail either a complex set of rules or many cases, both of which complicate the matching of different cases, especially if there is considerable ambiguity in the questions and answers. A hybrid approach of rules and case histories mimics the approach used by consultants such as that detailed by Van der Voort, (1975). Therefore in the expert systems, failure cases histories/failure modes are stored as cases and the rules are executed independently whenever their conditions are met. These rule types are called *whenever-then* expressions (CBR2 Casepoint manual: Adding rules to Casepoint, 1995). For example *whenever* "the word weld was found in the description or answer to a question", *then* "answer question 53 as a welding component".

The written format for the rules is based on a text file (*.rul) with a standard layout. The rules are detailed below in section 11.4.

Syntax	Description	Meaning
//	Double forward slash	Indication a REM or Read statement to aid upgrading and understanding of the program.
0	Zero as the first number	Indicates that the expert system should check if the matching word is in the initial written natural language description entered by the user. (If there is another number then this relates the answer of a question, i.e. 1,2,3,4,5,6,etc.)
"steel"	The matching word and specific spaces in quotes	The matching word here is Steel. However, in addition to this word, any word with the letters "steel" will be recognised as a match. If there was a space at the back and front then the word would be considered whole. For example the word "weld", i.e. no spaces, would find words like welder, welding, welded, etc. However, " weld " finds only the word weld.
=>	equals and forwards arrow	This is a separation between the input and the response.
1, 2, 3, 4, 5, or 6, etc	question reference numbers	These numbers relate to questions which are answered when the search word is found.
" Alumi nium Alloy "	A question answer.	This is the answer given if the matching word was found. Here it would be "Aluminium Alloy"
;	Semicolon	A punctuation mark showing the end of the rule.

A full description of the programming rules is given in the CBR2 Casepoint Manual (1995). However, this allows the reader to understand the coding used to produce rules within the expert system as detailed in appendix 2, and maybe use this knowledge to produce other expert and rule based systems.

11.3.1 Errors in typed words

The task of typing involves considerable coordination. Thus, it is very likely that the user will make typing errors while entering the written natural language description. Ideally the possibility of this should be accounted for and programming techniques should reduce the effects of these typing errors. An example of a typical typing error is as follows: If the user wanted to add the word "Weld" as meaning to unite metals, the user might misspell it and write welled as in flowed up. Thus, one of the search words could be welled to mean a welded component. However, another person might state that "water welled up" or "that corrosion bumps on the surface welled up", thus it would be unadvisable to use "welled" as a search term. Therefore, a balance has to be made between covering all possible errors and keeping the expert system simple and workable.

11.3.2 Different words expressing the same concepts

So the expert system can answer some of the questions with the information contained in the case description, rules must be present which identify different words with similar meanings in the search description. Thus one keyword can answer several questions and one question could be answered by several different keywords. For example in question 53 "What is the primary process used in manufacture", if the component was welded then the expert system should relate to all welding terms. As can be imagined this is a considerable task, as within the expert system there are presently 28 terms related to welded components as detailed below in section 11. 4. Some examples are weld, flux, plasma, HAZ, oxyacetylene, etc. Also in question 53, the answer could be related to Forging which has 11 related terms, thus considering words that only related to forging was important and not to any of the other answers (Forging, Casting, Machining, Welding, Grinding, Extrusion, or Drawing, Flame cutting, Rivetted seam). Finding these associated words was helped by the "Thesaurus of Metallurgical Terms" (The Materials Information Society, 1992) and other literature as detailed in section 5.2(iii) of the feasibility study, together with the authors own knowledge background.

There is hardly a limit to the list of associated words as new techniques and a more detailed analysis will show. However, there is a limit to the effectiveness of this technique especially when it comes to upgrading the expert system with more cases, because if the expert system is

constrained by an extensive number of rules, it goes from being a case based reasoning expert system to a rule based system with all the associated reasoning problems as details in section 2.4.2. Thus the rules detailed in appendix 2 are considered the initial minium with further work required to find the maximum.

11.4 Further work

In analysing word usage to find common words to exclude from the search, it was felt that an improved list could be developed if a wider selection of data bases and textual information could be examined. Examples of this could include other failure analysis reports and on-line databases such as Compendex, Metaldex and First Search, etc.

There have been considerable programming problems in introducing the list of excluded words into the expert systems search routines. This has been due to compiling problems with Microsoft Visual C++ version 1.53. The list is taken as a *.sym file and converted into a *.rc file. Methods to simplify this operation need to be undertaken for a faster operation of the expert system.

The rules developed could be expanded to include other words from the initial description and linked to other questions. It is the linking of rules to questions which will give the greatest benefit so that one answered question would allow the answering of several other questions from the rules embedded in the expert system.

11.5 Conclusion

This chapter has shown how through the analysis of words used in failure analysis and within the expert system the diagnostic ability of the expert system could be improved. This has been done by the exclusion of words and the development of rules. Analysis of the frequency of words used in case descriptions allowed the identification of the most commonly occurring words. These were analysed carefully and words which did not aid identification or matching were excluded. The analysis involved finding terms which were either commonly confused and abused, similar words, homonyms, or filler words (articles, pronouns, conjunctions, preposition, and interjections). Additionally, nouns that did not, in any way, relate to failure analysis were also excluded.

The rules developed were mainly used to answer questions from the initial natural language description given to the expert system by the user. It was found that many terms related to a given failure mode, process, or environment could be developed into rules. Care had to be taken not to mix terms or associate a word with two answers in one question. There is a fine balance between trying to cover every eventuality and producing an expert system constrained to one given path of analysis in a similar manner to a rule based system.

Chapter 12 The development of multimedia failure analysis applications.

12.0 Introduction

The objective of the chapter is to understand the factors that determine how people operate and make use of computer technology effectively (i.e. human-computer interactions) and to translate that understanding into the development of failure analysis information presentation tools (multimedia applications) to help engineers/users ensure that the failure analysis expert system could diagnose engineering materials failure problems.

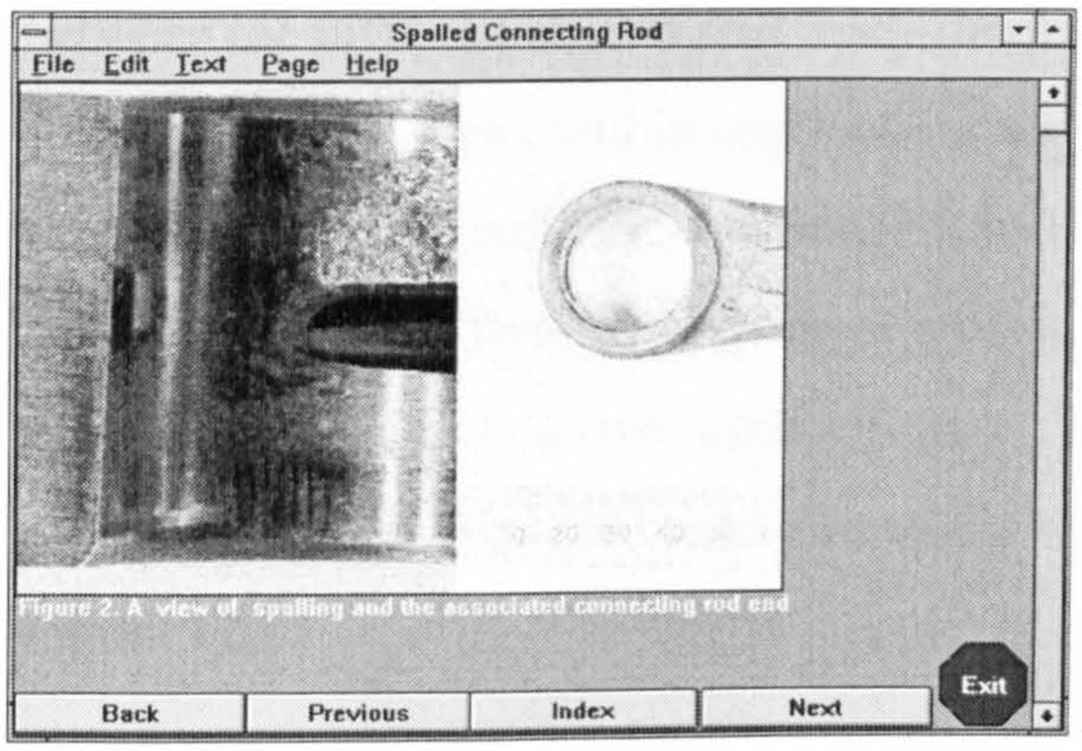


Figure 12.1 Spalling on a con-rod illustrated in ToolBook application.

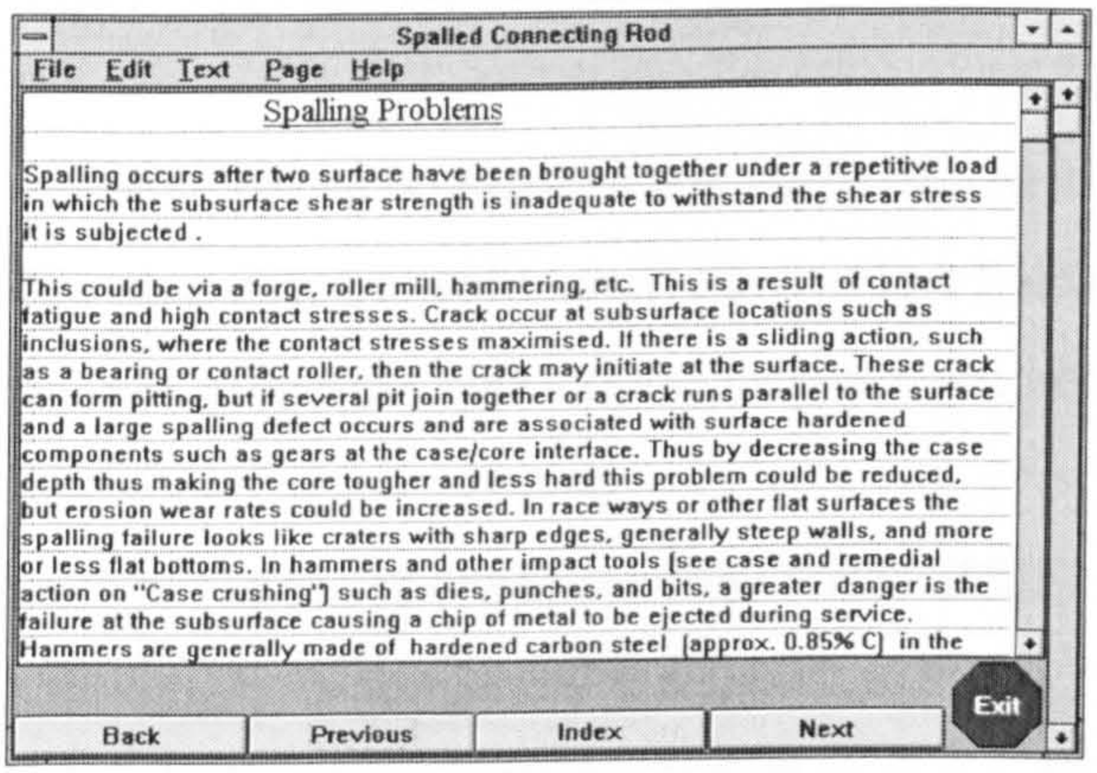


Figure 12.2 Typical text field detailed in Spalling ToolBook application.

As previously stated in section 6.4, ToolBook from the Asymetrix Corporation, was used as the front end graphical user interface (GUI) for CBR Express. The ToolBook interface contains scripts (programming codes) that link to ART-IM to ensure that knowledge acquisition and representation of the different case-bases is simple to execute. The original TOOLBOOK GUI can be extensively modified, to include functions more relevant to failure analysis. However, the main uses have been in the development of multimedia applications on different aspects of failure analysis. These are similar to electronic books giving further graphical details of different failure mechanisms.

The information provided by the multimedia applications is used to help the user of the expert system in understanding the meanings of different cases, actions and questions. For example if a user of the expert system found that the closest matching case was spalling, then the graphic browse facility in CBR Express would start-up the ToolBook application detailing "spalling" (Figure 12.1). The information provided by the ToolBook applications could be either graphical objects (i.e. photographs, diagrams, videos, clip-art, etc.), sound, or text.

Sound was not considered for the following reasons:- many computer systems do not have sound capabilities; many large institutions (Libraries) ideally do not want sound capabilities as this could disturb the environment in which the computer is sited; and the inclusion of sound can make the ToolBook files excessively large and unmanageable.

Although only graphical objects and text are involved in the applications, it is the links between the different objects that made them ideal in illustrating different aspects of materials failures. Typical links within applications are buttons that connect one collection of graphical objects and text to another collection. Each collection is held on a page and thus clicking a button is similar to turning the page of a book. Figure 12.1 shows a typical page that consists of two photographs and five linking buttons. When the next button is pressed, another series of photographs is displayed until eventually a text field detailing spalling appears as shown in Figure 12.2.

The links presented in Figures 12.1 and 12.2 are activated by a mouse click on visual buttons. This is only one type of linking. Another link used within the applications is Hot-words.

A hot word can be made of any string of text in a field. A hot word is a string of characters (a few characters, a word, or all the text in a field) designated as an object in its own right, with its own properties and scripts. Two or more hot words can appear in the same sentence, but no two hot words can overlap.

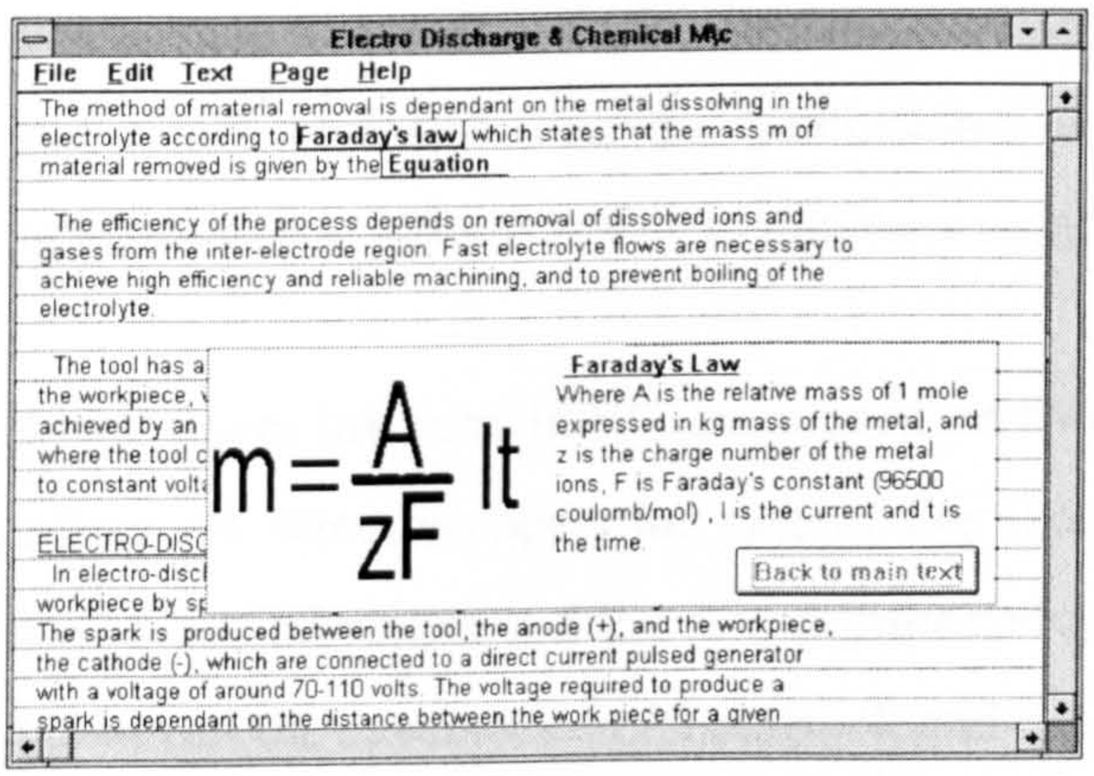


Figure 12.3 Hot words detailed in ToolBook Application on Electro-discharge and Chemical machining.

A hot word generates events and sends messages to other objects. Hot words function much like buttons, except that they are part of the text of a field. For example, hot word scripts can be written to enable navigation to another page in the application; to trigger animations; or as in Figure 12.3, to display a viewer to show the hot word's definition. In Figure 12.3, the hot word is "Faraday's law", on clicking this highlighted text, a box appears on the screen detailing Faraday's law.

12. 1 Issues involved in the development process

12.1.1 Introduction

In developing any computer package, a certain amount of pre-production planning is required. This is especially true when information is trying to be communicated as a multimedia application. In developing the different multimedia applications to communicate failure analysis information, several factors were found extremely important to the success of these applications. These are:-

Human to computer interaction

The software.

Software psychology

Ergonomical considerations

Cognitive ergonomical considerations

12.1.2 Human computer interaction has been defined as the "set of processes, dialogues, and actions through which a human user employs and interacts with a computer" (Baecker & Buxton, 1987, pp40). The goals of human computer interactions (HCI) are more relevant to the development of applications. These have been stated as: "to develop or improve the safety, utility, effectiveness, efficiency and usability of systems that include computers" (*Interacting with Computer*, 1989, pp3). The objective of this is to understand the factors that determine how engineers/users operate and make use of computer technology effectively, and to translate that understanding into the development of failure analysis information presentation tools (multimedia applications) to help engineers/users ensure that the failure analysis expert system is able to diagnose engineering materials failure problems.

Many issues involved in HCI have been set by using an IBM compatible computer running a Microsoft Windows operating system. For example the input commands are entered via a keyboard and mouse and the output information is displayed on a screen and in printed form. However, the capabilities of ToolBook and the requirements of the users allow many variations in interface design to be achieved.

12.1.3 The software. The practical possibilities of the software within the ToolBook application development tool are generally excessive to what is required by the users of the failure analysis expert system. For example, multicoloured flashing text is unnecessary and not suitable due to its distractive effect. Many developers are attracted to these facilities and use them excessively. There could be many reasons why these facilities are used excessively, albeit difficult to prove any of them. Ideally, the designer should consider only what is actually required by the user. In this case, failure analysis information, that is clear and to the point. This involves clear and relevant photographs and text.

12.1.4 Software psychology. What engineers/users expect or are presently accustomed to in computer systems relates to the users' perception, attention, memory, learning, thinking and problem solving capabilities. Within software design this has developed into the field of "software psychology" (Shneiderman, 1980). When engineers or users have experience in Microsoft Windows, they expect Microsoft Windows applications to work in a similar manner. If there is a complex series of commands to complete or they cannot preform simple Microsoft Windows operations such as copy and paste to aid their note taking, then the application will not be easy to use, and intensive on cognitive processes.

Humans are conditioned to find and absorb information in books and other printed documents. As the purpose of these applications is to provide information, it is ideal that this analogy is followed into the application design. This is where ToolBook has its strength over other applications, in that its structure and programming OpenScript language is modelled on a book. The buttons used in the applications have the following text Back, Previous, Index, Next. These symbolise turning back a page; turning to the previous page, going to the index, and turning to the next page, respectively.

12.1.5 Ergonomical considerations such as, mouse to keyboard input commands ratio, navigation commands. For example, a poorly ergonomically designed interface would require many keyboard manipulations and the command structure would require several individual commands to complete a single task. A better ergonomically designed interface could achieve the same task in one mouse click. Additionally, it is commonly known that excessive keyboard or mouse manipulations, can lead to repetitive strain injury in users. Therefore the

applications must work with the minimum number of manipulations and ideally these should be mouse (commands) based. In the design of these applications this means careful consideration being given to the structure of the system.

12.1.6 Cognitive ergonomics is an emerging discipline which focuses particularly on human information processing and computer systems and aims to develop knowledge about the interactions between human information procession capacities and their limitations and technical information procession systems. The knowledge gained should support the design of these technical systems, and the design of education and other kinds of support" (PMT 607, 1990) (EACE, 1987). For example, there is an ideal speed at which information should be provided to and by the user. If a graphical object or text is displayed too fast then the user will be unable to comprehend the information, whereas if the application is too slow, the attention of the user will be strained. This ideally means that applications will load as fast as possible and only change when required by the user. Applications generally require buttons, menus, and hyper-text links, however, if these are excessive, i.e. all the commands on one screen or commands not required for the application, then cognitive confusion and muscle strain can occur. Therefore, applications should only have the minimum number of buttons, menus, and hyper-text links required by the user to perform the task. Typical design decisions are how many buttons, what size are these buttons, where is it appropriate to use buttons or hot words and where do they link.

Colour used within a design for buttons, text, backgrounds, boarders, and icons can be extremely useful or distractive. Thus, careful colour combination selection is important. The simple solution to this problem would be to use the Microsoft Windows standard colour selection. However, this itself is not ideal and is boring. The application has to look different in a minor way to differentiate it from other Windows applications. The colour could also be very different between different pages. This is not ideal because it does not allow the user to identify the application. If the design was extremely different on each page the user could think that the application has changed, and thus would not seem to flow.

12.1.7 Examples of other multimedia packages

There is a growing and extensive collection of multimedia packages, most of which have been designed to be educational and entertaining, and are based on CD-ROM format. Typical examples are Microsoft Encarta Encyclopaedia and Microsoft Cinemania. There are no commercial multimedia applications directly related to failure analysis. However, as detailed in chapter 3, there are multimedia applications related to failure analysis involving corrosion, e.g. (Trethewey and Keenan, 1994), (Bogaerts and Agema, 1992) and in materials selection (Ashby et al, 1995a, 1995b) (Waterman et al, 1992) (Institute of Materials, 1997). These applications are purpose-built for a small professional audience rather than the majority of applications which are for more general audiences. Differences in design can be observed between these two distinctive application types. Both try to be as easy to use as possible. However, the language used in the professional applications is not suited for the general applications. The general applications are generally better visually designed; this is due to the financial resources available at the design stage which can be invested in the development. These systems rely on their visual appearance to be successful in the marketplace whereas the professional applications are generally task specific and rely on their ability to solve problems or provide correct and relevant information. This sometimes means that the interface design could be improved, although this could be purely superficial and not required nor expected by the professional users. In the majority of professional applications, the addition of flashy and complex graphics can be seen to be distracting to the purpose of the application, Therefore, these applications tend not to use these facilities that are possible in their development tools. Thus, professional applications tend to use more standard and simple graphics to undertake far more complex information processing.

12.1.8 Conclusion

Although the hardware and software package had been decided in chapter 6, there are many variations that could be applied. However, as the purpose of these applications is to transfer information efficiently, an investigation into the different influencing factors and an examination of different software packages was required before any clear design principle could be established. This design principle is to have the minimum requirement for the required information delivery. This covers everything from the computer hardware to the design graphics. For example, the ideal scenario would be where the application held no file

space, loaded instantaneously, held all the relevant information in a simple to use and easily understandable graphical user interface. In reality that means decisions about the applications, structure (i.e. links, pages, orientation, navigation, shape), colours, objects (buttons, hot words, links, graphics, text) and their arrangement.

12.2 Typical resulting applications

The actual applications are listed in the table below. Although not an extensive number of applications have been developed, it was the knowledge engineering exercise involved in development that will enable many other applications to be arranged and produced in a similar manner.

File	Title
dezinc.tbk	Dezincification
electr.tbk	A comparative assessment between Electro-Discharge Machining and Electro-Chemical machining.
ferry.tbk	Corrosion Fatigue of overlay welded shaft on a ferry stabiliser fin.
H2ojet.tbk	Abrasive water jet and water jet cutting.
Mast.tbk	Delamination in an aluminium sailing mast.
seacat1.tbk	Failure of impeller on a large ship due to fatigue at repair weld.
Spalro.tbk	A spalled connecting rod.
Valve.tbk	Overheating and corrosion of an exhaust valve .

Table 12.1 The different ToolBook applications developed.

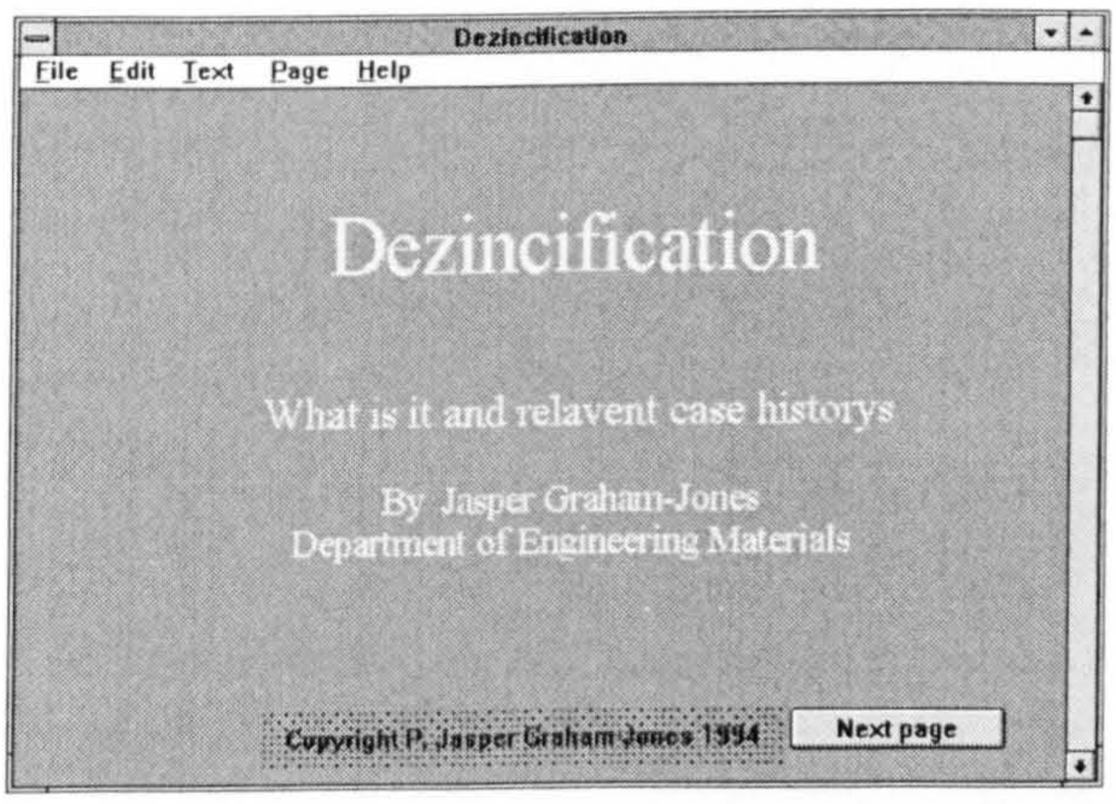


Figure 12.4 Typical start-up page in ToolBook applications.

The following screen shots have been taken from several applications to demonstrate the issues raised in section 12.1, on the different design decisions taken during development. Figure 12.4 details a typical start-up page for an application. The text is clearly stating the exact nature of this application and a clear indication for the next step is given on the "Start" button which has a contrasting colour to differentiate it from the background. The copyright text is coloured differently from the

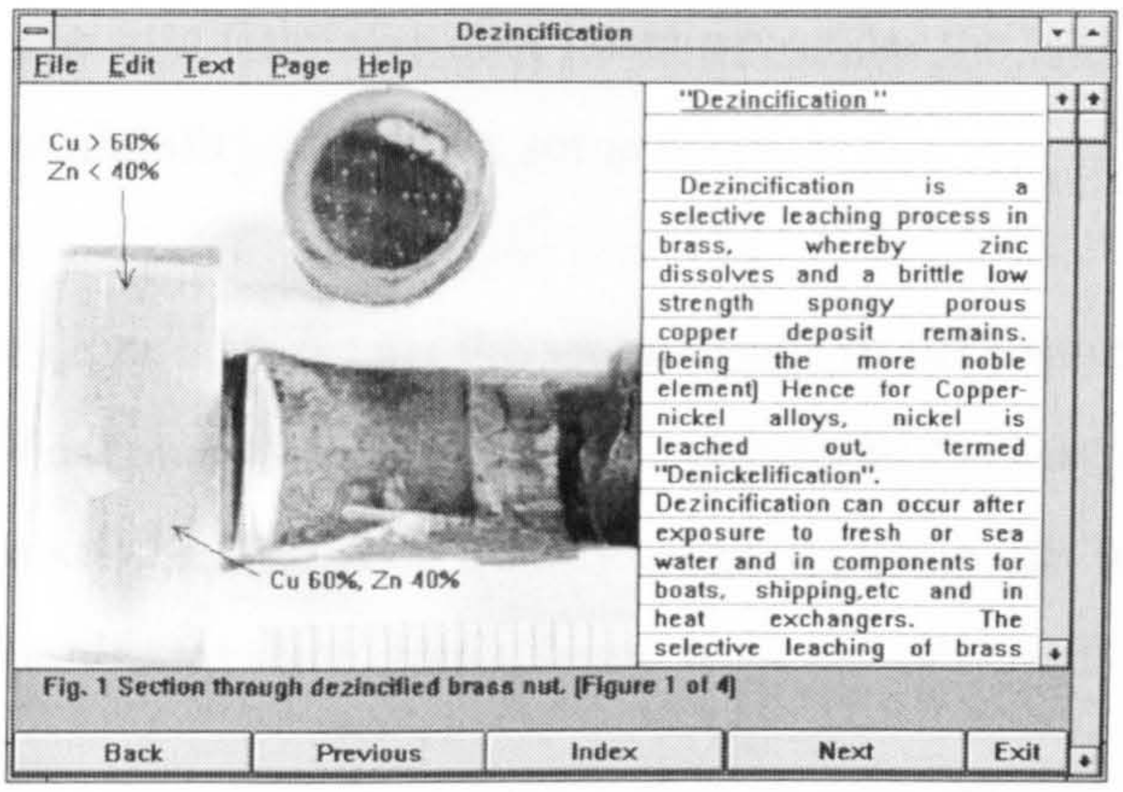


Figure 12.5 First page of Dezincification ToolBook application.

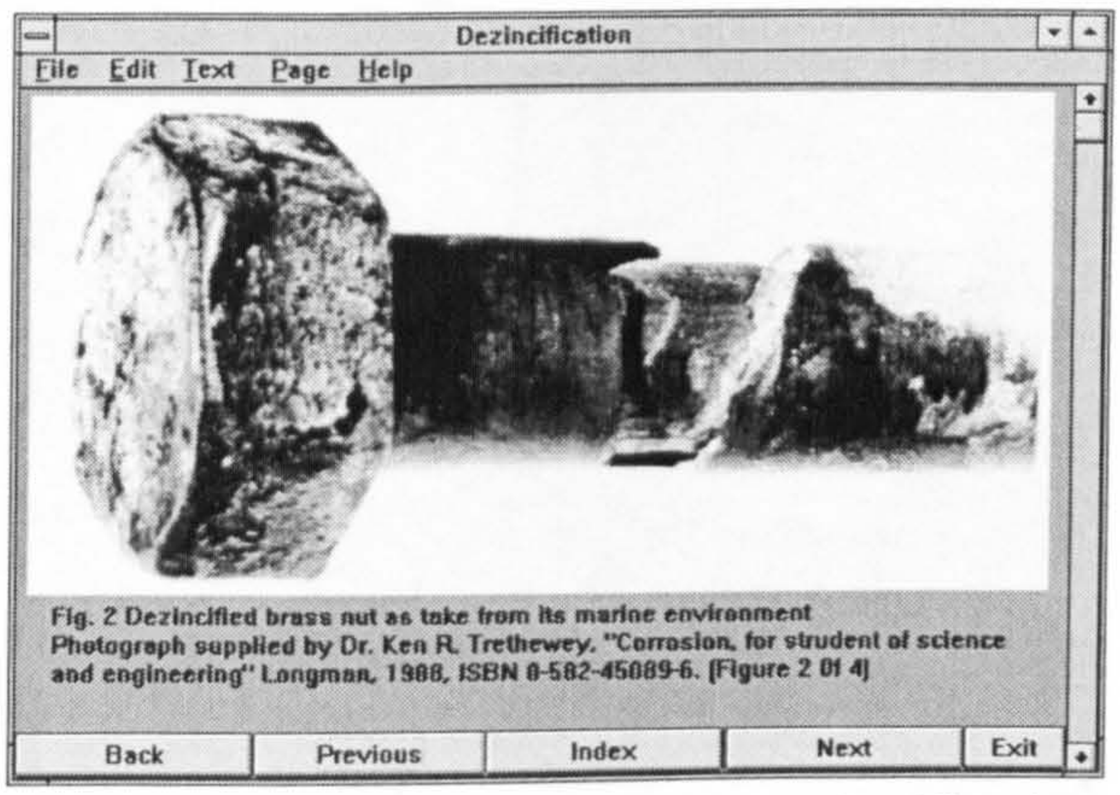


Figure 12.6 Second page of Dezincification application.

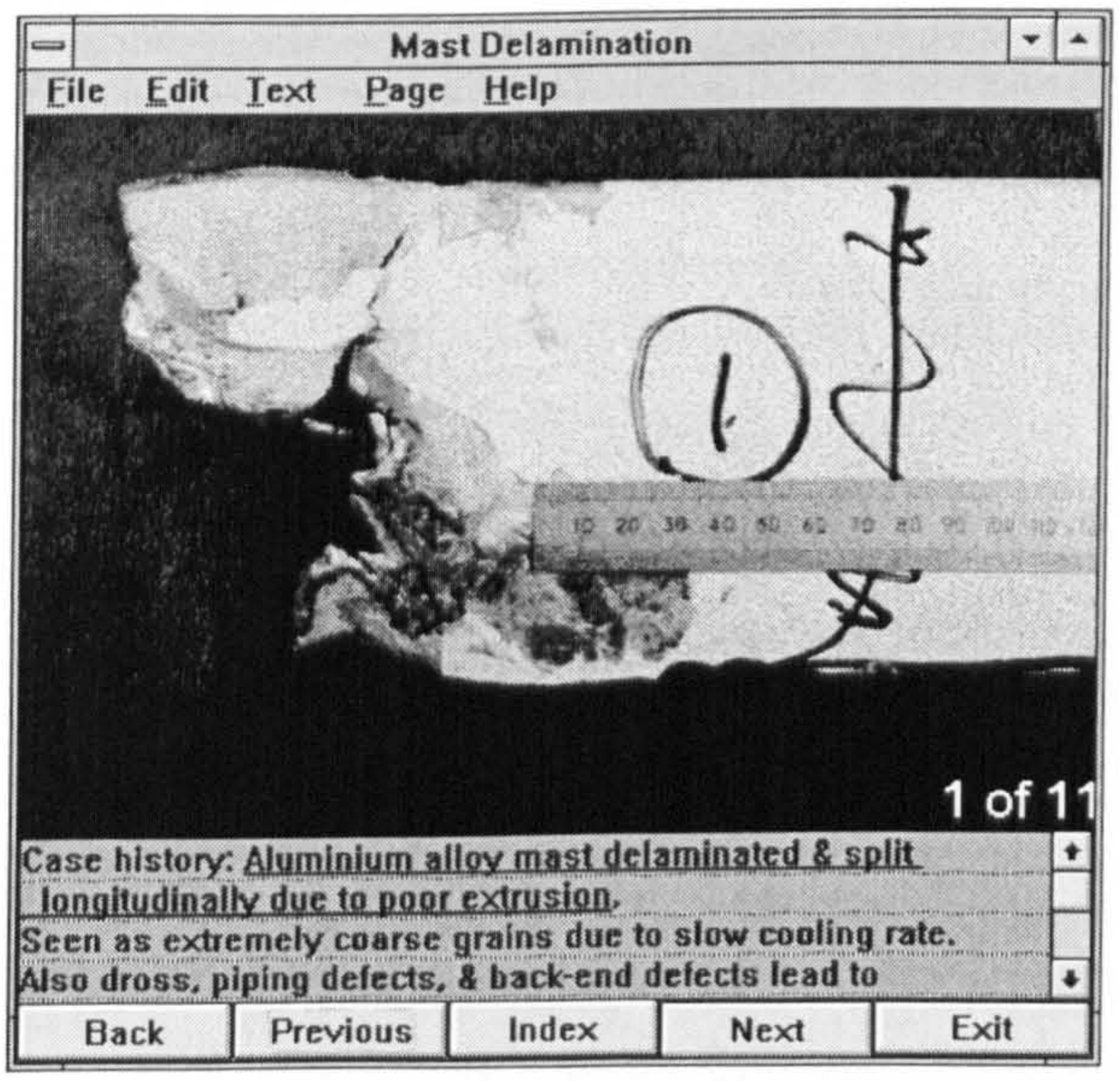


Figure 12.7 Detailing Mast Delamination application

other text indicating it is a hot word linked to information on the copyrights involved in this application.

Figure 12.5 details the first page of an application on dezincification. Note that the buttons reflect the book metaphor and their placement depends on probability of greatest use. The next button changes the Window frame to the next page and is placed on the right-hand side, similar to turning a page; the end button ends the application and as the majority of users are right-handed, it is also on the right-hand side; both the next button and the end button are placed next to each other as they are likely to be the greatest used buttons; the index button will link to a glossary of terms; the previous button goes back to the last page viewed; and the back button goes back one page. Also note how the start button is in a similar position to the next button. This combination of buttons is the most likely to be used, so by placing the start button over the next button means fewer movements with the mouse which reduces repetitive strain injuries. The diagram is labelled with contrasting colours for readability and the figure caption also details which figure this is with respect to the total number of figures. The text field has a scroll bar which allows a greater amount of text to be displayed on one page, i.e. the text field scrolls up allowing more text to be viewed.

The text field also uses baselines under the text. It is well known that base lines improve the readability of text for some users.

Figure 12.6 details the second page of the Dezincification application, where the photograph was taken from a published source and thus the copyright permission was granted for this instance. The good quality of the image is due to the original photograph, rather that the published photograph, being used and scanned.

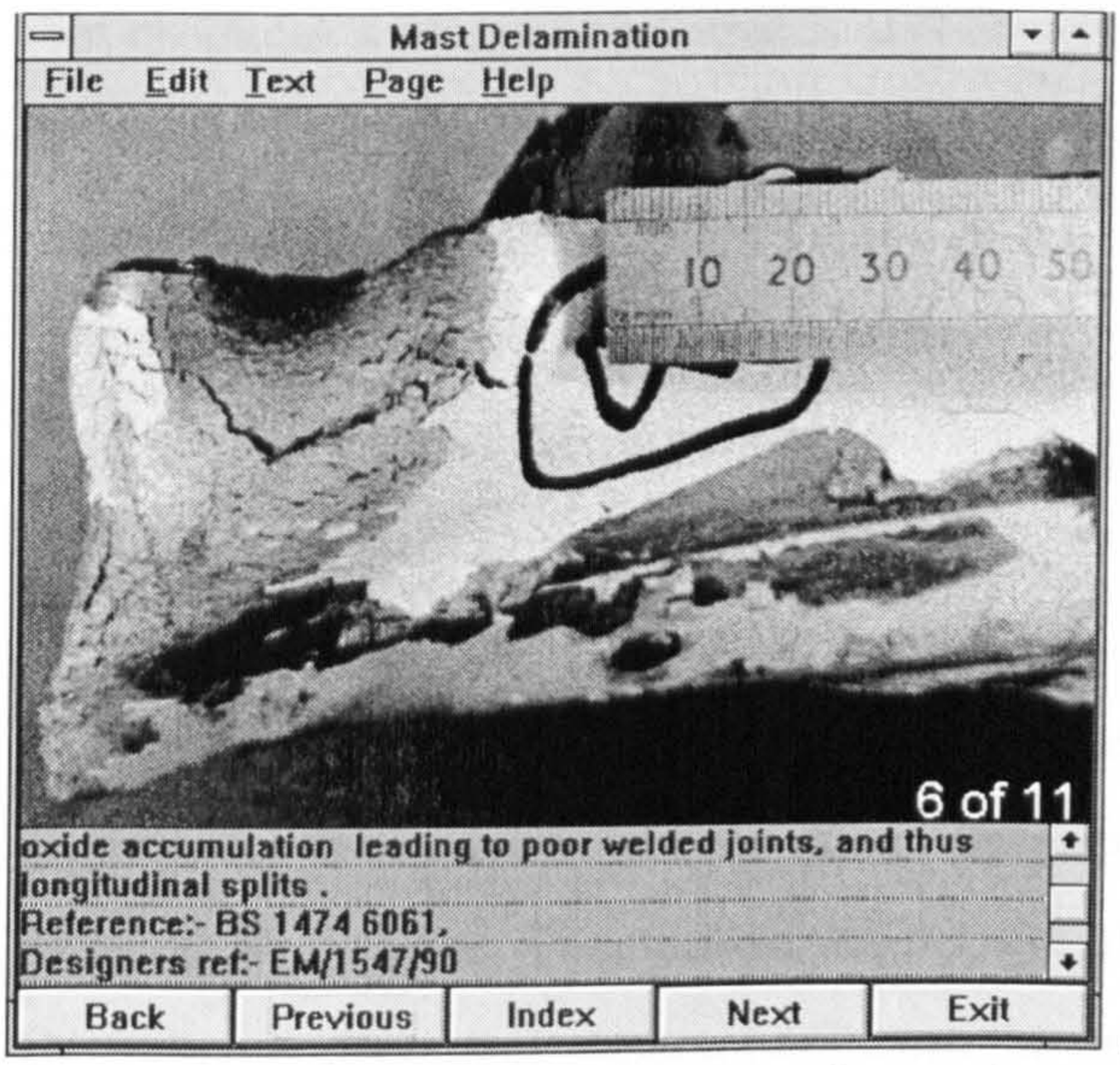


Figure 12.8 Image 6 of 11 from Mast Delamination application.

Also note how the standard Microsoft Windows menu has been kept with all its functions. It is possible to edit the functions in the menu to either include more or fewer functions. More functions would over complicate the application. Within these applications it is very unlikely that some users would require the full functionality of the standard menu. However fewer functions would make the user feel uneasy (see cognitive ergonomics, section 12.2) as it would not be performing how a Windows program is expected to preform. Additionally, the colours of the menu bar, title header and scroll bars are set to the users own default setting within their computer.

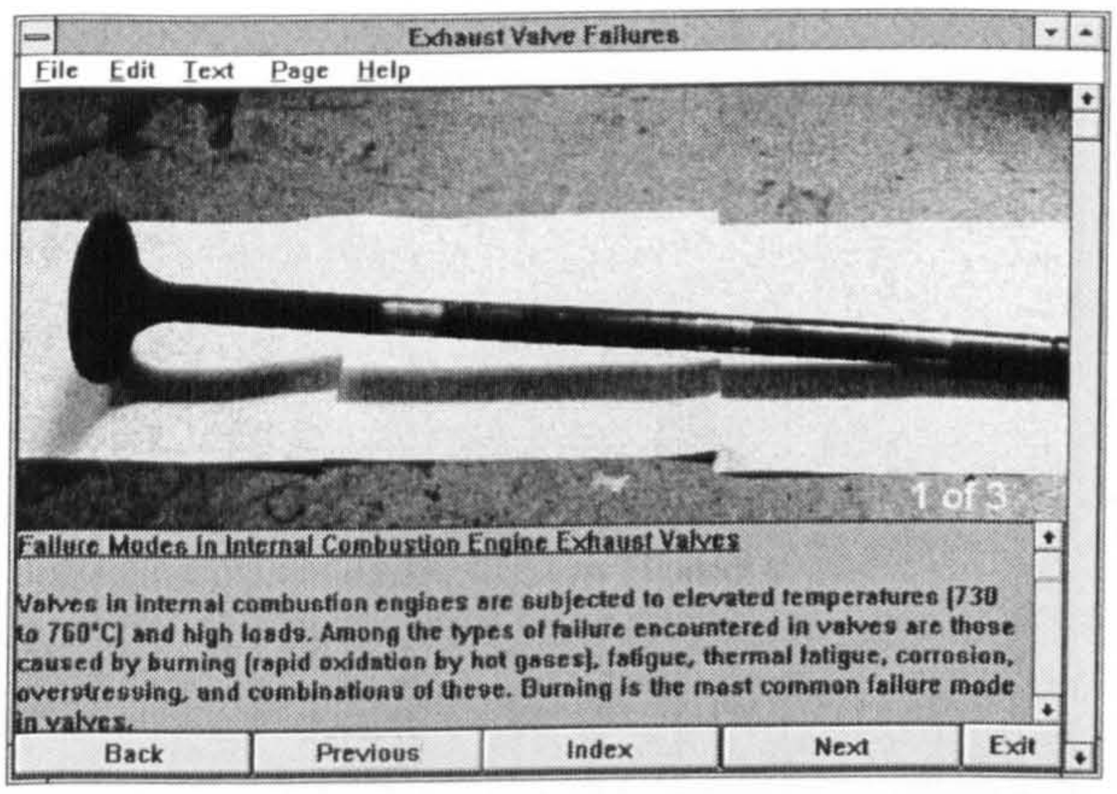


Figure 12.9 Applications detailing a typical exhaust valve failure.

Figure 12.7 details another application illustrating a case from the Engineering Materials Consultancy Service file. By using these photographs copyright issues were simplified. The application shows a series of photographs and related text on the delamination of a yacht's main mast. The photographs are arranged so that each successive pages show greater detail of the failure. The button

arrangement is similar to the previous application (Figures 12.4 to 12.6). This allows the user to become accustomed to the layout and thus comfortable which makes the arrangements seem easy to use. Other similarities include the text field with a scroll bar and baselines; and the indexing of the screens (i.e. 1 of 11).

The quality of the printed screen images does not reflect the quality of the screen image itself. To increase the applications speed, the quality of the photographs is reduced to a minimum that produces a screen image that is still clearly detailed but cannot be magnified. This also means that the printed screen image is of less quality than the original screen image due to degrading of the image. This might not appear ideal, as the user might want a copy for himself, which is still possible although a poorer quality. However, it does reduce the likelihood of an image being copied without copyright permission.

Figure 12.8 shows greater detail of the delamination and reference details. The two references included in this application are for the user. The British Standard reference is a normal material reference. However, the other reference is a reference to the Engineering Materials Consultancy Service. The number relates directly to the case, but only Engineering Materials Consultancy personnel or personnel from the organisation who requested the original report will have this information. This allows for backtracking of errors and traceability of sources.

Figure 12.9 details another application for valve failures. Presently this application only gives text details of all the typical failure mechanisms and visual photographs of one type of failure, (burning) but given the resources (photographs, diagrams, etc.) more failures could be included.

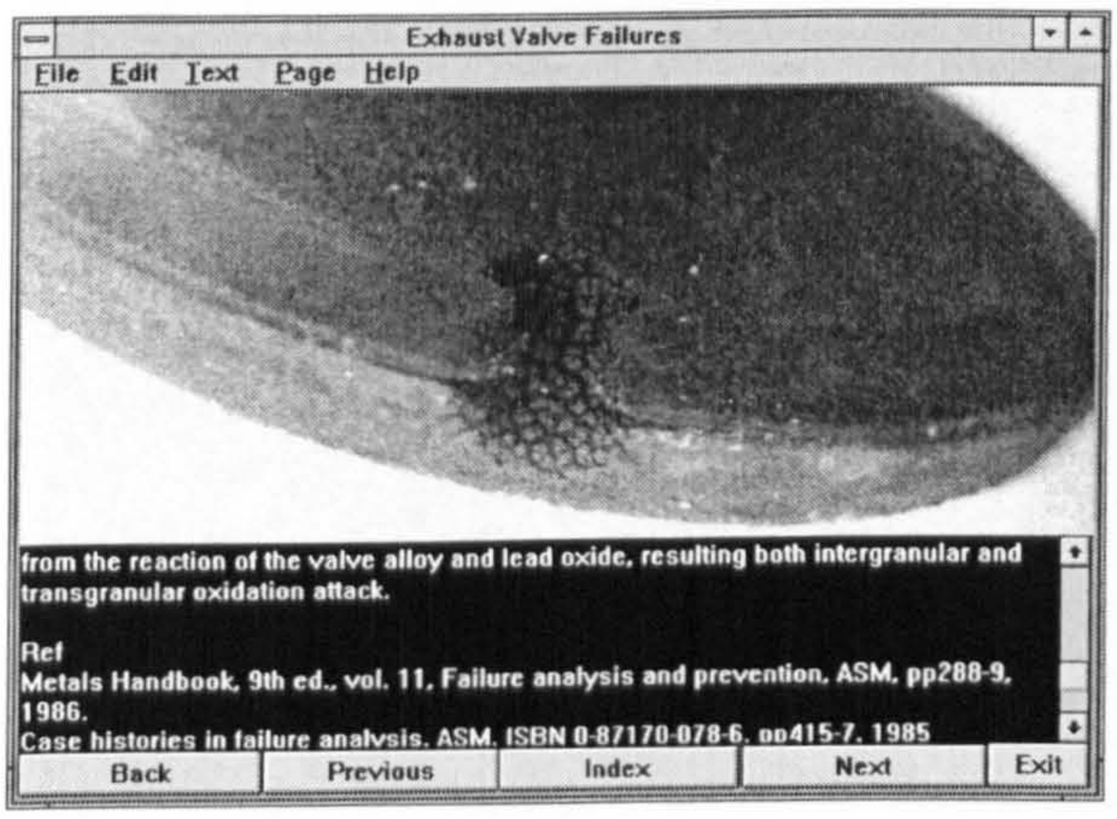


Figure 12.10 Second image in application detailing typical exhaust valve failures.

This figure and application illustrate, that once the general structure of an application is arranged, further additions and developments are much easier. This is also true with a common layout between applications.

Although there are still minor differences between the applications, these are generally due to the main resource (i.e. the photographs)

and their different sizes. Note the similarity between this application (Figures 12.9-12.10) and other applications (Figures 12.1 to 12.8).

Figure 12.10 shows the second image in the typical exhaust valve failures applications. Note the increased magnification used to detail the failure mode and the two references given for further research.

Figure 12.11 shows an exit window used to check whether or not the user wishes to exit from the application. This in some respect is very useful, especially as the "next" page button is adjacent to the "exit" button which could have been pressed by mistake. However, exiting this application will require more mouse and finger movement; this increases the strain on the user. Thus in the applications shown in Figures 12.1 to 12.10, no exit windows were used, but rather a smaller "exit" button and a large "next" button are provided. The small size of the "exit" button makes it less easy to press this button accidentally.

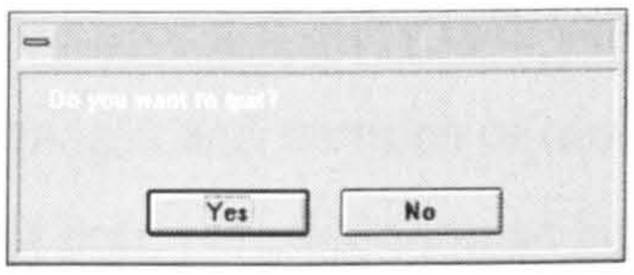


Figure 12.11 Exit window

12.3 Upgrading information

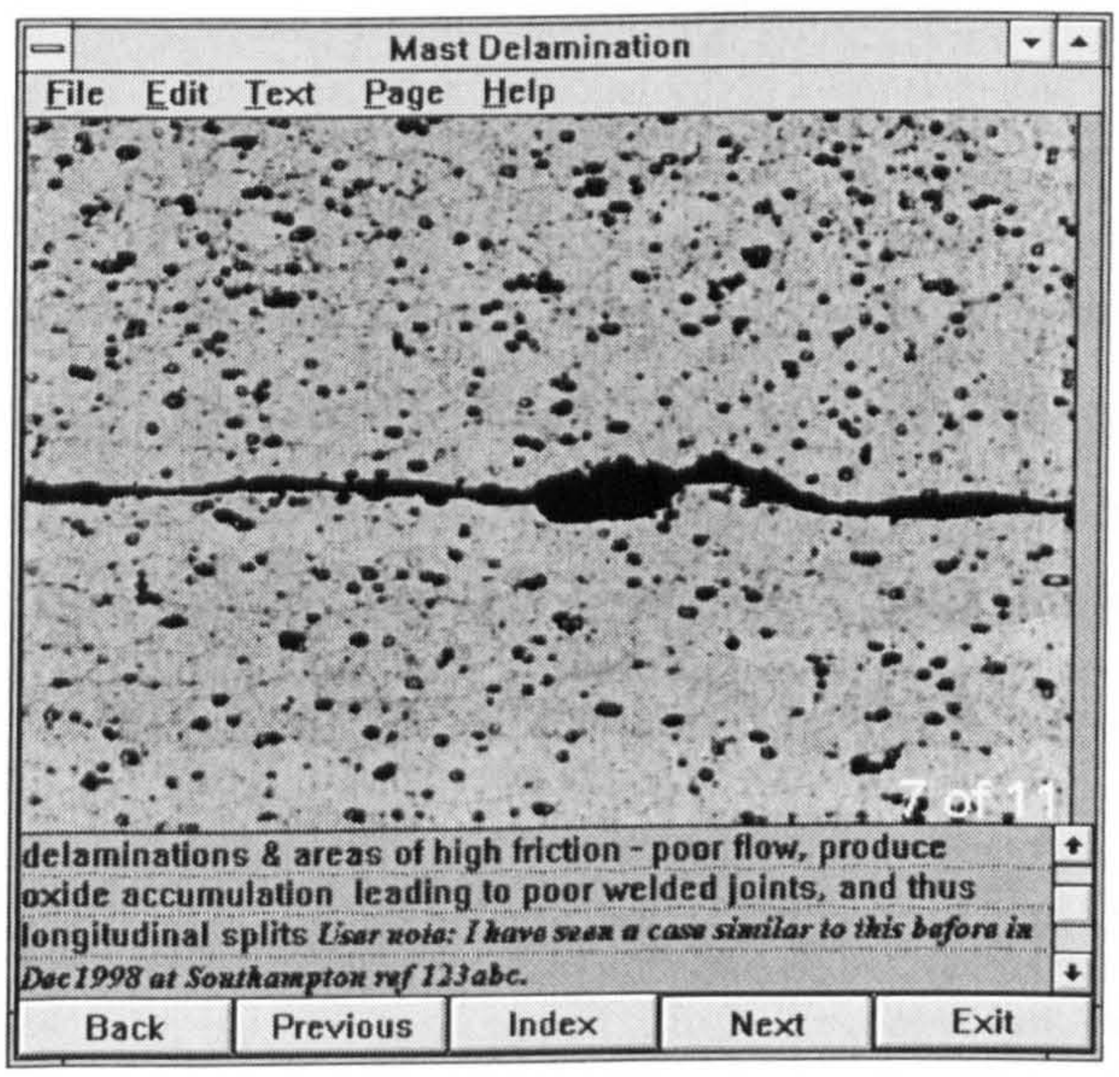


Figure 12.12 Editing the text in the applications.

Upgrading any application is a major problem. One method which allows upgrading is to allow users to include notes themselves. Although this facility is not presently available with all these applications presented in section 12.2, the capability is included where the text fields are not considered as a background. The editing facility is based on a standard Windows arrangement. This can be observed in the menu bar, i.e. (File, Edit, Text, Page, Help) of Figure 12.12. The underlines are included so that users without a mouse can run these programs by pressing Alt and F, E, T, P, H respectively. Ideally an application detailing a

failure mode could be added to with references to the users own work and experiences. In the text field in Figure 12.12, an example is given where the user has written "***User note: I have seen a case similar to this before in Dec1998 at Southampton ref 123abc.***". Italics and bold text have been used to differentiate it from the original text. However, all standard fonts and styles are possible. Although the original text is the same on all eleven pages, when additions are made, then these are linked to the page in which they were done. This means that the user could add notes directed at the graphical objects rather than the original text.

12.4 Difficulties in development

A major difficulty in developing any application that involves many different graphical images and sections of text are the copyright issues. If it is wished to use an image or section of text, permission must be granted from the owner, else it is illegal. With these applications all the images have either been taken by the author, or owned by the Engineering Materials Consultancy Service, else the owner of the copyright of the images has given permission for their inclusion. So although there are many interesting and useful images and sections of text, being able to use these can be problematic. Thus it is preferred to make, draw or write the appropriate images or sections of text. This poses problems, because to collect all the photographs, drawings, graphics and text requires considerable effort. This has curtailed the development of many more applications.

12.5 Future work

Presently there are only a few applications, mainly due to the limited resources available and the time required to develop others free of copyright. Further work in collecting these resources is paramount for the successful development of these applications. This could either be via collecting permissions from copyright holders or ideally by making original resources (photographs, drawings, diagrams, graphics, icons, and text).

With the future development of other applications for different aspects of failure analysis and with the uses of new application development tools, changes in design are very likely. When development of these multimedia applications started, it was with version 1.5 of ToolBook. However, since then version three and now version four of ToolBook are available. Each version brings more tools that are easier to use. An example is in the embedding of graphical

buttons which was very difficult, though possible, in versions 1.5 but in version three extremely easy. A decision on whether or not the older developed applications can be updated or the newer applications kept to the older but well known style has to be undertaken. In this development, the problem is not great because no applications have been sold commercially. The decision about changing or updating just because it is possible might become a marketing decision. Further analysis of these factors and development need to be considered in the future.

Although these applications successfully transmit information, more complex applications will be required in future systems to detail more complex information. This might include applications which undertake mathematical problems such as fatigue life prediction, corrosion rate prediction and stress/strain overload prediction. The system has been designed so that any of these may be included at some future date. This has been helped by allowing and using independent and self-standing applications. Therefore each application could be programmed in either TOOLBOOK, Visual Basic, Hypertext markup language (HTML) or another application able to work on its own but linked into the Failure analysis diagnostic expert system.

The use of the Internet could take over in this area as detailed in chapter 14. However, the design principles and structures are the same. Thus transferring these applications to web based applications could be simply undertaken if required. However there are situations where this is not ideal, for example, to sell the information; to lower hardware overheads, to control the structure and images to protect either your name or copyrights; etc. Thus, standalone applications such as these presented in section 12.3 are likely to be still useful in the future.

12.6 Conclusions

The objective of the chapter was to understand how people operate computer technology effectively, and to translate that into the development of information presentation tools to ensure users of the expert system could diagnose engineering materials failure problems. ToolBook was used as the programming tool which linked together different graphical objects and text via hot words and buttons. This was not as simple as first thought and after

examining how humans interacted with computer systems, with special considerations given to the software, software psychology, ergonomics, and cognitive ergonomics, a general design principle was determined. This design principle is to have the minimum required computer/software facilities for the required information delivery. This meant the following design principles were used:-

1. The start-up page clearly states the applications' topic and indicates the next step.
2. Button links were used in a manner that reflected the book metaphor of turning pages over.
3. The placement of the buttons was standardised and ordered depending on likely use and the right-handed user.
4. Contrasting colours and base lines were used to aid readability.
5. Standard Windows design principles and functions were included, i.e. a standard menu bar(file, edit, copy, paste, etc.).
6. Original photographs were used where possible and these were reduced in definition to increase the loading speed and to reduce the possibility of coping.
7. References to both bibliography and to the Engineering Materials Consultancy Service were included.
8. The sequence of graphical objects, i.e. photographs, drawings, etc. should follow in an ordered discussion with images increasing in magnification.

With the common layout and general structure arrangement decided, the major difficult in developing applications is in collecting copyright free images and text relevant to the applications. By either producing the images and text ourselves or being granted permission from the copyright holders, part of this problem can be solved. However, this is an extremely time consuming and complex task that affects both multimedia and world wide web applications.

Chapter 13 Evaluation

13.0 Introduction

Expert systems are developed from basic guidelines, codes of practice, and past experience (failure case histories). These are less stable sources of information than conventional computer systems which are based on algorithms developed from natural scientific laws, or established professional or business practices. For a successful expert system, evaluation of this less stable information and its structure is important. Evaluation is considered as an on-going process which ideally produces better diagnostic decisions from the expert system.

Evaluation requires a systematic approach, and realistic judgements as expert systems are formulated from human knowledge (basic guidelines, codes of practice, and past experiences). Case based reasoning expert systems need more evaluation after initial prototype development as less structured information in the form of cases, questions, and action, is incorporated into a case based reasoning expert system. With a rule based expert system, errors in design and structure are more easily found because these few errors are more catastrophic to the working of the expert system. However for a case based system, if a case (failure mechanism) is inappropriately matched with either a question or an action, the expert system will continue working whereas the linear approach used in rule based systems means that one miss-placed or miss-directed rule could cause the system to stop working. Thus in a failure analysis case based reasoning expert system, evaluation after the initial prototype development involves the correct assignment of cases, actions, and questions with respect to each other.

13.1 Initial evaluation methodology

The first evaluation was initiated to see whether the case base reasoning methodology was suitable for the problem of failure analysis in engineering metallic materials. With minimal failure analysis information added to the case based reasoning shell, it became clear that due to the complexity of failure analysis knowledge, case based reasoning was considered the best reasoning methodology (Chapters 2 and 4). This is summarized by the following features:- Easy to develop, use, and up-gradable because case based reasoning does not require an explicit domain model and so elicitation becomes a task of gathering failure case histories and identifying significant features that describe a failure. Thus using case based reasoning does

not require the programming of exact rules, or procedures which is difficult in failure analysis. Also large volumes of information can be managed and learning can be by acquiring new failure case histories.

Evaluating a case based reasoning expert system is ideally an iterative process as each new section of information is added to the system. Thus, before accepting a new case, question or action into the case-base system an initial evaluation was carried out by the expert system's author. Initially there was little planning in the development of the different cases, actions and questions, but it became clear that this was more important than originally envisaged. The main plan revolved around a list of the most common failure modes (Section 8.3) from which cases could be developed. However, before committing the plan to the case-based system, a few checks were made on the information, as outlined below. These checks were formulated from the experience gained in developing the expert system.

13.1.1 Is the title unique and informative?

The title should describe the case naturally but briefly. However, this is not easy especially in very case specific failure mechanisms when a long description is needed such as " *Brittle fracture due to Strain-age embrittlement in a mild steel hook*". If the case title was for a more general failure mechanism, then a shorter description should be used, such as " *Brittle fracture*". Although brief descriptions are ideal, if the description is too short then several descriptions could look similar. Also when modifying a search case to create a new one it is easy to forget to change the title. Thus during evaluation it is important to check whether several different cases have nearly the same title.

13.1.2 Is the case useful?

Once the case is correctly defined, the final step is to reconfirm that the case is useful. Within the thesis there has been great deliberation over this especially concerning very specific failures. In a generic failure expert system, the cases should generally be very broad and applicable to any component. However it is very difficult to find very generic information (component or manufacturing process or user independent) without inventing it, but it is important not to define new cases just because the 'wrong' raw material is available. Within

the expert system some cases are very general and some very specific; with this balance both general and specific cases would be identified if a search match is found. If the search case is not similar to any specific case then it should be matched against a general case. For example, "Hydrogen cracking from hydride formation (Titanium)" is a case specific failure where "Hydrogen attack" is a general failure. Ideally the search for the case specific failure would result in both these cases, and the general case would be the result of a less matching search, but would give the user the opportunity to examine the other related cases. With the inclusion of more cases with time, the expert system should improve. Through the expert systems development shell, a test case button is used to see if there is already a case available that closely matches the new case and whether it has the same or very similar actions. Normally it is not worth duplicating a case that already exists. Duplicate cases should be archived instead of indexed.

13.1.3 Is the description complete and useful?

The best descriptions are of moderate length (five lines) and state the key features that are reconfirmed by the questions and their actions. It is easy to add more information because it is available, however keeping the description to the same length helps the matching algorithm. As previously stated in Chapter 11, some words are excluded from the search, thus there is little point in adding these excluded words to the description, but it is better to concentrate on rather words that describe the failure. For example in the failure case "Brittle fracture due to Strain-age embrittlement in a mild steel hook" the description is as follows:-

> The hook conformed to B.S.482, & used in an overhead hoist in a foundry.
> Failure was initiated at pre-existing crack defect, due to poor manufacture.
> Then exposure to radiant heat from molten metal and being plastically strained would lead to strain-age embrittlement. Thus a ductile material would become brittle & notch sensitive. *British engine boiler & electrical insurance technical report 1965, Vol.VI, pp81-87*

The filler words used are so the description is written in clear English. The description, however could be a list of descriptive words related to the failure mechanism.

13.1.4 Are the actions appropriate?

As stated in Chapter 10, many cases share actions and one case can have several actions. If a case was found to have more than about four associated actions, it was important to review the case due to the possibly of more than one failure mode being within the case. The multiple actions, could all be remedies for the same failure situation, if not, it either indicates that the cases themselves were not split into individual failure mechanisms, or it may imply that the remedial actions were broken up too finely. In development, this problem was tackled by only writing actions when required and if required by a case and after an extensive search of the different actions already written.

For example the action "Stress concentration factors and how to reduce them" is associated with three different cases, one of which is "Tooth-bending impact and shear failure of gears". This case also has two other actions "Tooth-bending impact and shear failure of gears" and "General overload failure prevention (& fatigue failure prevention)". This interrelationships can be difficult to track and thus continuous evaluation during development was considered important.

In developing and evaluating, it was found that the expert system software works better when cases identify single problems that have single solutions. Many situations in failure analysis exist however, where a failure problem has two or three solutions associated with it.

13.1.5 Are all of the questions necessary?

With the many different fields of information in failure analysis, it would be possible to ask a question for each. This would lead to an extensive list, which would be difficult to answer due to the excessive time and knowledge required. Taking into account time considerations, the maximum number of questions was set at 50. The value was arbitrary although suggested by the CBR Express reference manual. In further evaluation of this arbitrary number of questions, it was found approximately correct but a lower number of questions would have been ideal purely on maintenance considerations, i.e. a greater number of questions causes an exponential increase in maintenance. This is true when one question is associated with most cases, as this will involve each case being edited. If the number of questions is too small, not

enough information will be considered by the expert system to allow it to diagnose the failure situation. Thus in developing the different questions, an upper limit was set i.e. fifty, and the information required was fitted into this level. When initial trials were undertaken with the expert system, many users were concerned about the number of questions that they perceived they would have to answer. However, the expert system only considers the top five matching cases and asks the questions associated with these cases. Thus not all questions are asked and not all questions need to be answered to diagnose the failure situation.

The most difficult problem in developing and evaluating questions, is trying not to ask too many questions but rather to ask a few pertinent questions because it is very common to put too many questions in a case, particularly if using a database or existing decision tree as a starting model. However, when working with unstructured knowledge such as failure analysis, it is easy to either overlap questions or not ask for the required information. Thus both during development and evaluation the following check list was devised for a critical assessment of each question.

1) Is the question really necessary to diagnose the failure situation?

2) Is there a similar question in which this and other questions could be combined to ask for the same information? i.e. do any of the questions overlap? It is best to offer the search operator only the minimum number of questions to answer because overlapping questions are time consuming, and may cause confusion in cases where they are used separately. For example, if there are several questions asking if the material is copper, steel, zinc, aluminium, this would be both boring and tiring. A better questioning strategy is having one question which asks "what is the material?" and the user picks from a list. An analogy of this situation would be like a automatic teller machine (cash machine) asking if you would like another pound or asking the amount required. Thus, paring down the question list to a truly functional set is extremely important.

3) Are there any questions missing? When dealing with the un-structured knowledge associated with failure analysis, having missing questions is a considerable problem. With

structured knowledge, the user knows what information is required and thus what questions to ask. Failure and failure analysis is complex and unstructured at present (Chapter 4). So to understand which questions are important an understanding in failure and failure analysis is required. Attempts at this have been made by the author, however there is no definitive correct questioning strategy. This problem is further complicated if there are several similar failure cases in the data base, because questions have to be developed which will distinguish and confirm these cases. A method suggested by the author to help reduce this problem was to examine the case descriptions to see if some fact was not verified by a question.

4) Are the expected answers to questions correct? With the restrictive number of questions set to fifty, many questions were used in most cases. Thus when associating questions to a new failure case on an existing, similar case, it is very easy to copy an inappropriate answer. For example, stress corrosion cracking in one material is very similar to another. However, the question relating to what the material is could be copied from the other case incorrectly. Thus it was found important to check each question and answer in turn.

13.2 Initial evaluation results

From the initial evaluation, a case-based reasoning methodology was considered to be the most appropriate failure analysis expert system methodology.

The evaluation of the cases in the case-base was based on the questions in section 13.1. The following was found:-

a) The uniqueness and usefulness of each case was based on a survey of books, journals, and other references on the common modes of failure (section 5.2(iii)). One case was designed for each failure mechanism subgroup, thus keeping the cases unique and useful.

b) When it became time to link questions to the case, no extra questions were developed until all the previously existing questions were analysed to see if they would be appropriate. In this way questions did not overlap each another.

c) The questions were kept to a minimum by combining them with other questions. One method of combining the questions was by using a list question rather than many "Yes/No"

questions. This proved very successful and it was decided that this method of combining was useful and thus should be developed further.

d) It is difficult to know at this stage of development whether there are any cases, questions, or actions missing, but this is a major part of the on going evaluation. It is better to have missing cases, questions, or actions, than incorrect information. To ensure that the information gained from publications was correct, it was crossed checked against other publications (see list of references at back of thesis).

e) The main problem was due to the large amount of information that was required to initiate the system and to have enough questions and actions to use, as both would be shared by the cases. As the expert system developed, more questions were made available. This meant that cases developed later would have more associated questions and thus more likely to be found in a search. To reduce this problem required editing of initial cases as entered so to include more associated questions.

f) Editing a case was relatively simple, however, editing either a question or action would mean editing each associated case. Such a situation was undertaken when several questions were revised from 'Yes/No' to list type questions. This task was extremely time consuming.

13.3 Evaluation by Users

Initially, evaluation was carried out by the expert system's author as an ongoing process during development. However, as many errors may be missed by the author because he has formulated the system on his knowledge and understanding of the problems of failure analysis and the workings of the expert system. It is useful for evaluation to be undertaken by other experienced engineers. Several opportunities arose for others to test the expert system. These were during an exhibition at the University of Southampton and during a NACE Corrosion conference, 1996.

13.3.1 Evaluation at 'Multimedia Week' Southampton University, 1994

The exhibition was to show the different expert systems and multimedia systems within the engineering faculty at Southampton University. This was a part of "Multimedia Week 1994" (23 November) developed in conjunction with the University of Southampton Academic Staff Development programme, the Interactive Learning Centre and Computer Services. Initially the author demonstrated the expert system to several engineers and non-engineers. Then three expert engineers used the package with no help or guidance from the author who left the room. Only one expert had a very basic understanding of how the system worked. This was done to see if the interface was intuitive to use.

The experts found the expert system easy and intuitive to use. The demonstration and trial by the experts was a good method of evaluation. When the author was demonstrating the expert system, the response was very positive, especially towards the graphical user interface and the natural language interface, which provided an easy access to the system. This is very important to an expert system. Several good comments on the graphical browsing facility were expressed, such as its appropriateness as an educational tool. It was thus concluded that more graphical browse facilities will be developed for the next edition. This involves the scanning of images and the writing of more detailed text.

The main problem found during the evaluation at the exhibition was that cases were too specific and referred one particular failure case rather than being more generic, and that questions asked for information that had already been given within the natural language description in the search case.

The reason for the cases being too specific was that they had been obtained from real failure case histories from the Engineering Materials Consultancy Service. The consultancy service is an organisation which analyses complex, and specific failure situations. Thus the different case histories are likely to be specific to a particular failure mechanism, e.g. 'Hydrogen embrittlement failure of maraging steel bourdon tubes' (Mellor, 1994). It could be argued that having very specific cases is ideal as this is a means of making available the knowledge within the consultancy files and unusual failure cases. The pretext being that it is the unusual failure cases that engineers would want to investigate. However as found during the

evaluation engineers need to find generic failure cases. These generic cases might only be useful as a check against the engineers assumptions. After further discussions with the Manager of the Engineering Materials Consultancy Service (Dr B.G. Mellor) and others as detailed in section 5.2(iii), many of the failure investigations undertaken were requested by engineers and managers, in which the diagnosis was easily interpreted by the consultant. Thus for an expert system to be useful to engineers meant that a more generic and educational approach was required. Therefore the solution was to increase the number of generic cases and associated information.

When questions asked for information that had already been given during the natural language description, it made the expert system seen less intelligent to the users. The problem identified was more difficult to solve because questions were added to confirm the description in the first place. The author thought that this would be helpful to the users and it also helped in searching for the correct case. So if these type of question are not to be included in the system a new approach was required. Two possible approaches were examined, Firstly to rewrite some questions so it did not seem that the same information was being sought and secondly to include rules which examine the natural language search description. Both of these solutions were used. The questions were edited to ask for more direct information (Chapter 9) and the rules were developed as detailed in Chapter 12. However a more radical approach was to develop several different case-based systems all linked together. These would then be accessed by a simple rule-based system.

For example:- Question:- What is your component?

Shaft

Lifting Equipment

Springs

Sliding Bearing

Tools and Dies

From this list, different failure modes relating to the component would be accessed via a group of failure cases relating to that component group. Component groupings are shown in the section 8.4.

For example if the user, had chosen a spring for the list of component then the expert system should indicate fatigue as a possible mode of failure because the majority of failures in springs are caused by fatigue. However, it is more important in the subsequent failure analysis to consider the reasons for initiation rather than the final outcome. The initiation of cracks could come from a variety of causes, and these would also have to be indicated by the expert system, as possible failure modes, such as unusual operating conditions; processing errors and deficiencies; material defects, and in occasional exceptions poor design quality. As well as fatigue, relaxation is another major failure mechanism in springs, with its own initiation reason which would also have to be flagged up by the expert system.

Another example of this process is shown if the user had picked sliding bearings as their component, which has the following failure mechanisms:- Wear, Foreign particles, Misalignment, Fatigue, Cavitation, Fretting, Electrical erosion, Corrosion (corrosion fatigue failures).

Although this method of multiple expert systems is good it will involve considerable overlap in cases, actions, and questions, if the present expert system shell was to be used for this application. However, if a more object oriented programming method was used (Microcosm or HTML) then it is envisaged it would work.

13.3.2 Evaluation from conference delegates

During NACE Corrosion 96 Conference (24-29th March 1996) in Denver, Colorado, USA, another evaluation was undertaken by conference delegates. Most delegates evaluating the expert system were taking part in Computers in Corrosion Control: Modelling and Information Processing (T-3U) Symposia and thus could be considered to have above average understanding in computer systems. These delegates are also likely to be more critical in their evaluation.

The delegates, expressed considerable differences in opinion as to the viability, approach and effectiveness of the expert system, although the majority of comments were positive and all delegates were constructive in their criticisms. There was no standard questionnaire, but examples, of comments by delegates are given below, although their names have not been included, as no consent has current been given and their statements have not been confirmed by themselves.

Delegate A.

He was a professional software developer who worked in corrosion but had little experience in undertaking failure analysis. He had developed his own knowledge based system on object oriented programming. He saw that his system was better for this and any other task and could not understand the purpose of the research. He found that the expert system worked well, however suggested that this task could be done with any software program. I explained to him the problems involve in knowledge acquisition of failure analysis information (Chapter 4) and the capabilities of case based reasoning to cope with this problem (Chapter2 and 5). He considered the idea of an expert system for failure analysis extremely good, although he also saw the problems involved and appreciated the complexity of the problem.

Delegate B

She specialized in database design and structures, and thus was interested in the reason for the use of case based reasoning for failure analysis. She asked why had not a standard database not been used. Standard databases required the knowledge to be well structured which is not the case for failure analysis. So after discussing the problems of initial knowledge acquisition and the unstructured knowledge involved, she agreed that the route taken was suitable. She also concluded that there were immense problem involved in building such a system.

Delegate C

He had some previous experience in developing expert systems from rule based reasoning techniques. He explained the many problems faced by such system, such as difficult maintenance, limited updating, and poor diagnostic ability. It was explained that only case

base reasoning was able to cope with these problems, without it the expert system in its present detail would not be feasible.

Delegate D

He was a speaker at the conference presenting a paper on case based reasoning and failure analysis. He discussed the problems of language and the importance of setting up a structure for this and future expert systems. His research was more generic than presented in this expert system. However, he believed the expert system, case based reasoning and failure analysis were an ideal combination. He also indicated that this expert system, like any case based reasoning expert system would be held back by the acquisition of failure case histories. However as discussed previously, failure analysis knowledge is highly unstructured, and thus difficult to build in to a expert system. He believed that the research undertaken was worth while and some what difficult to complete in the time scale. The was also agreed and the solutions detailed in this work discussed.

13.4 Evaluation by other software developers

On two occasions a detailed analysis of the expert system was undertaken by software developers. One was working in a company developing a materials selection expert system, in conjunction with Greenwich University were he was registered for a PhD thesis (Tyler, 1998). His materials selection expert system was specifically designed for one product range in a company. He wanted to investigate the ability of this expert system compared to his developed system. And to investigate if the two systems could be integrated together. He wanted to link the selection of materials to products and the possible resulting failure modes from this selection. He found that the expert system worked well and there was a possibility of integrating the knowledge more so than the expert system shell, as he found that the shell for his expert system was similar to CBR Express although not a true case based reasoning system. However he believed that the expert system was an interesting approach to a difficult problem, in which the present expert system was very successful in diagnosing failure cases.

The other developer was an engineering student undertaking his final year project at the University of Southampton (Rempault, 1998). His project was divided into two sections.

Firstly an assessment to test the efficiency of the expert system and secondly to determine if any improvements or extra information was required. To evaluate the efficiency of the expert system, nine cases were selected at random from Handbook of Case Histories in Failure Analysis (ASM, 1992) and these known cases were compared against the predictions from the expert system.

The results showed that establishing a correct initial description was important to the success of the search. The more similar the search description is against the case base then the better the matching. The production of an accurate description will depend on the user of the system. Although rules and excluded words help in diagnosing failures, the expert system is limited in its ability and like all computer systems takes information and facts literally. So the correct and consistent terminology together with a full description. As he found it was important to "state the situation completely and clearly, and resist the temptation to write descriptions that are extremely short".

He found the careful answering of questions was helped by the additional information included with most questions as mistakes in response can be easily made.

He found that the results were very much dependant on the number of cases in the expert system. As most searches produced very similar matches. I.e. although the search case might not have an exact matching cases in the expert system, the next similar matching case was given. Only very complex or specific cases caused problems because the expert system is either unable to match the cases or produces an incorrect answer.

In many respects this diagnoses problem could be solved by the inclusion of many extra failure case histories. However, this is possibly impossible because each failure is different is some way from all others. Thus all possible solutions would have to be included, this would be an impossible task. It is for this reason that in the design of the expert system a structured approach was used to cover the majority of general metallic failure mechanisms rather than every conceivable failure mechanism. In extremely complex failure situations, multiple failure mechanisms are common. As the expert system works by the diagnosis of single

failure mechanisms, analysis of these complex failure situations is problematic if not impossible. There are presently no known solutions to this problem apart for the addition of failure case histories which emphasize the different aspects of multiple failure mechanisms.

He concluded that " A good failure analysis should be based on the interpretation of the results given by the expert system and not directly from the results. For the moment, (metallic) materials failure analysis is still to complex (to take over the position of a human consultant). However, this expert system is an excellent tool, and allows a non-expert to practise efficient materials failure analysis.

13.5 Real failure case trial diagnosis.

To illustrate the expert system working, a real failure is examined. It is hoped that both attractive features and possible areas for improvement within the expert system can be illustrated.

13.5.1 The failure case history.

The real failure involved the disintegration and disappearance of a copper washer used as part of a sealing system for a cooling tube in sea water. The copper washer was used in combination with a 316 Stainless steel bolt, holding a rubber diaphragm and a stainless steel end capping. The end capping was attached to the stainless steel cooling tube by the bolt which threaded through the washer, the capping and through the diaphragm which like the washer sealed the main stainless steel tube end. The washer's environment was sea water at 25°C. However, inside the cooling tube the pH was about twice that found in sea water. The client's description was that washers on several bolts had completely disappeared and on others had become brittle and considerably reduced in size. It had previously been checked that washers had not been forgotten during manufacture and thus some form of deterioration had taken place. This deterioration was believed to be corrosion because this was the only failure mechanism known to the client which causes wasting of the material. It was ascertained from the clients that copper washers were used because the ductile properties of copper would allow deformation of the copper under the tightening action of the bolt and

hence seal the joint between the bolt and the end capping. This is standard practice in many areas, such as sump plugs in car engines.

13.5.2 Initial search

In the initial search the following description was used, and this produced the output detailed in the Table below:-

'My washer made of copper on stainless steel has corrded in sea water'

Questions answered	**Answer**
What is the primary process used in manufacture?	Machining
What primary component group is your component?	Mechanical Fastening
Is there a source of hydrogen in the component environment?	Yes
What is your primary material?	Stainless Steel

Table 13.1 Initial search using description which answer questions using rules

Top Ten Cases	**Score**
Sulphide stress corrosion cracking	24
Gaseous corrosion in 300 series stainless steel	24
Brittle cracks in steel due to low cycle fatigue from preexisting crack	23
Sulphide stress corrosion cracking in pipe lines	23
Stress corrosion cracking in 300 series stainless steel	22
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin	22
Impeller failure due to repair or build up welds with pores	21
Caustic cracking due to poor rivetted seams in a steel ships' boiler	19
Hydrogen pressure cracking in pipe lines	18
Dezincification and denickelification	18

Table 13.2 Resultant cases from first search

This output (Table 13.2) is the result of rules which were fired from keywords in the initial natural language description and by matching the initial description against descriptions in the case base. The keywords were; *washer, copper, stainless steel, corrded, sea water.* One keyword (corrded) was

deliberately incorrectly spelt in the initial description and thus was not available as the keyword 'corroded' and unable to fire a rule to answer the question *'Would you consider the environment was corrosive in any way'*. Therefore, it is not shown in the list of questions answered in Table 13.1. However, this is not a considerable problem because the question will be asked directly from information given in the description and from the answered questions. It is the expert system's fuzzy searching ability that allows for such errors where the resultant matching score will only differ by reducing all corrosion related cases by 2% in similarity matching. To make the analysis harder for the expert system the spelling error was left in and the diagnosis continued. Further detail illustrating how this spelling error has effected the failure diagnosis is given later in section 13.5.5 and Table 13.8.

13.5.3 The response of rules.

It is interesting to note that even though three materials were stated in the description it was the middle material keyword (stainless) in combination with the last material keyword (steel) to be mentioned that answered the question *'What is your primary material?'* with stainless steel. This is because each word is examined in turn and so the question *'What is your primary material?'* was answered three times. Firstly, with the answer copper, then steel (carbon steel) and then finally with the words *'stainless steel'*. This order can be changed by changing the order of the rules directly in the *.rul file. Thus if the author preferred that the answer to the question was copper rather than steel, then the rule relating to copper would have to be first or placed before the rule for steel. The decision as to the order of rules is complex as each movement in placement will affect the whole system. Thus, decisions should be based on a case by case basis. In this case, knowing that the material was copper was more important, but this does not consider the whole expert system which has many different cases related to stainless steel failure. However, the concept that copper is still important to the investigation is not lost, because the similarity matching of different descriptions has indicated that dezincification might be a problem. Dezincification is also supported by the keyword: sea water. What the expert system does allow, is for the operator to change the responses that the computer has developed.

Questions answered	Answer
What is the primary process used in manufacture?	Machining
What primary component group is your component?	Mechanical Fastening
Is there a source of hydrogen in the component environment?	Yes
What is your primary material?	**CARBON STEEL**

Table 13.3 Change of primary material to Carbon Steel.

Top Ten Cases	Score
Sulphide stress corrosion cracking in pipe lines	23
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin	22
Gaseous corrosion in 300 series stainless steel	21
Sulphide stress corrosion cracking	20
Hydrogen attack	20
Hydrogen embrittlement failure of maraging steel bourdon tubes	19
Caustic cracking due to poor rivetted seams in a steel ships' boiler	19
Impact spalling in steel	19
Hydrogen pressure cracking in pipe lines	18
Dezincification and denickelification	18

Table 13.4 Resultant cases from change to Carbon Steel.

Changes in the order of rules can dramatically effect the different cases produced as seen in Table 13.3, where the order between stainless steel and steel was changed so that the keyword *'Steel'* became the most important and hence the question *'What is your primary material?'* was answered by carbon steel. The results shown in the cases and the matching scores (Table 13.2) are considerably different, in that some cases have been replaced and others have changed their order and matching scores. Drawing conclusions from these initial results is difficult as far too little information has been provided for the expert system to make a valid judgement of the correct failure mode. However, it is encouraging that the expert system has associated several corrosion problems and marine applications to the description.

13.5.4 Answering questions.

To gather more information, more questions suggested by the expert system need to be answered. The order of the questions relates to the order of the cases and the questions associated with the first five cases.

The first step is to confirm that the answer to questions suggested by the expert system are correct for the situation. Confirming or changing the answers is shown up on the computer's screen by a change in answer colour from light blue to black. In this case the question *'What is your primary material?'*

could be changed from stainless steel to Copper alloy as it is the copper washer which has been affected. This decision is typical to failure analysis as an assumption has to be made as to the failure origin. Some failures might be the result of other external factors, which could lead to secondary failures which could be seen as the origins to the first failure, i.e. did the aircraft wing fall off in flight or did it break off when the aircraft hit the ground?.

If as suggested above the answer was change to Copper alloy (Table 13.5) then similar changes such as that seen by changing the rule order (Table 13.1 to 13.4) can be seen in Table 13.6.

Questions answered	Answer
What is the primary process used in manufacture?	Machining
What primary component group is your component?	Mechanical Fastening
Is there a source of hydrogen in the component environment?	Yes
What is your primary material?	**COPPER ALLOY**

Table 13.5 Change of primary material to Copper Alloy

Top Ten Cases	**Score**
Sulphide stress corrosion cracking	23
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin	22
Gaseous corrosion in 300 series stainless steel	21
Sulphide stress corrosion cracking in pipe lines	20
Hydrogen pressure cracking in pipe lines	18
Dezincification and denickelification	18
Impeller failure due to repair or build up welds with pores	17
Brittle cracks in steel due to low cycle fatigue from preexisting crack	17
Electrostatic discharge attack on a thrust bearing	17
Stress corrosion cracking in aluminum alloys	17

Table 13.6 Resultant top scoring cases where material is Copper Alloy

At this early stage of the investigation, limited information is given and thus changing one question or keyword will affect the resulting matched cases, as seen by Tables 13.1 to 13.6. Although considerable change in the order between cases is observed, little change is seen in the range of scores as detailed in Table 13.7.

Question "What is your primary material?"	Range of scores for top ten matching cases
Stainless Steel	18-24
Carbon Steel	18-23
Copper Alloy	17-23

Table 13.7

These differences are not sufficient to guarantee an accurate match between cases but it does indicate possible failure mechanisms (cases) to be investigated further. Some of these can be simply ignored by the fact that accurate information has not been given to exclude the case. Others might not seem possible, yet they cannot be excluded while others might be highly possible. Clearing your mind of any preconceived conclusions is important at this stage, and to evaluate what the expert system is considering. Firstly 90 cases are being matched against six keywords which have answered four questions. This being so, it is not surprising that the expert system arrives at many different conclusions. When other human experts in the field of failure analysis evaluate a given failure mode, they have one failure mode in mind, and when the expert system does not quickly narrow down the cases to that single failure mode the human experts consider the expert system to perform poorly. This is a limited view of the expert system as it is considering all the possibilities to all 90 stored failure cases. Thus, from the limited information, many cases might be possible. However, as more questions are answered, an improved accuracy in matching is produced. Thus, several extra questions were answered. These additional questions as shown in bold are detailed in Table 13.8.

Questions answered	Answer
What is the primary process used in manufacture?	Machining
What primary component group is your component?	Mechanical Fastening
Is there a source of hydrogen in the component environment?	**Yes**
What is your primary material?	Copper Alloy
Would you consider the environment was corrosive in any way	**Yes**
Has the failure occurred before the part went into service	**No**
Does the surface look like a fatigue failure	**No**
Is there extensive plastic deformation around the fracture site	**No**
Before failure was the surface in good condition free from any initial defects	**Yes**
Does the affected area have less strength than the parent material	**Yes**
What level is the stress, (High, Low, or No load)	**No load**
Is stress an important consideration in this failure	**No**
Did the failure occur at room or a higher temperature	**Room Temperature**
Does a liquid flow past, through, around, or next to your component	**Yes**
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)	**No**

Questions answered	Answer
Has spalling or delamination of the surface occurred	**Yes**
Are two different metals touching each other	**Yes**
Does a gas flow around or through your component	**No**
If the fracture surface is examined are there any subsurface defects	**Not Answered**
What is your secondary material	**Not Answered**

Table 13. 8 Answering further questions shown in bold.

Top Twenty Cases	Score
Galvanic Corrosion	45
Micro biological corrosion	44
Gaseous corrosion in 300 series stainless steel	40
Stress corrosion cracking in 300 series stainless steel	38
Electrostatic discharge attack on a thrust bearing	38
Cracking from precipitation of internal hydrogen, (Fish-eyes)	35
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin	33
Contact corrosion, welding with more or less noble electrode	33
Sulphide stress corrosion cracking in pipe lines	30
Crevice corrosion	30
Flow erosion in pipes	30
Hydrogen embrittlement failure of maraging steel bourdon tubes	29
Hydrogen induced blistering	29
Pitting corrosion	29
Hydrogen pressure cracking in pipe lines	28
Stress corrosion cracking in 70% Cu, 30%	28
Decarburization of steel	28
Impeller failure due to repair or build up welds with pores	28
Hydrogen attack	27
Sulphide stress corrosion cracking	27

Table 13.9 Top twenty cases from answering a total of twenty questions

After these first twenty questions have been answered, galvanic corrosion has been diagnosed (Table 13.9). However, there is a very small (1%) difference between the top two cases. At these early stages of diagnosis, the expert system is sensitive to the results of answering questions. For example, if a question is not in any way related or not specific to a case; then during development of the expert system the author did not associate that question to that case, i.e. *"'Are there any cracks perpendicular to the tensile stress'*, in the case of galvanic corrosion, the direction of cracks is not a major issue in the propensity for galvanic corrosion. Hence the question and case are not associated, but when this question is answered it will add to the matching scores of all the questions associated with it. Thus these associated cases, will increase in their matching. This could mean that initially

galvanic corrosion might be replaced as the lead failure diagnosis by another case. However, when this is tried, due to the compelling evidence and the strength of the current diagnosis, the expert system still indicates that galvanic corrosion is the main failure mechanism, although the scores have changed as detailed in Table 13.10 below

Question	Not Answered	Answer Yes	Answer No
If the fracture surface is examined, are there any subsurface defects	47	51	49
Are there any cracks perpendicular to the tensile stress	47	46	46

Table 13.10 The effect of answering different questions individually on the matching score for galvanic corrosion.

From Table 13.10, the effect of answering the questions, relates to the questions' association with a failure case. If the question associated with the case requires a positive answer to increase the probability for galvanic corrosion (i.e. YES) as in question one (table 13.6), on answering *'yes'* would increases the matching score by the matching weighting and answering *'no'* would increases the matching score by the mis-match weighting. The different weightings are set by the expert system's author during development and maintenance. The actual values relate to the author's opinion of the importance that each question has on the propensity for all failure mechanisms. In the question *'If the fracture surface is examined, are there any subsurface defects'* the matching score is 26 and the mis-match score is two. These values are fixed and affect all associated cases in a similar manner. Further details are given in section 9.4 and methods to improve the accuracy are given in chapter 15 on Datamining.

Match value	Mis-match value	Not Answered	Answer Yes	Answer No	Range of scores for Yes & No
1	0	52	52	52	0
26	0	47	54	49	5
52	0	47	55	52	3
78	0	45	56	45*	11
1	2	52	52	52	0
26	2	49	51	49	2
52	2	47	55	52	3

Match value	Mis-match value	Not Answered	Answer Yes	Answer No	Range of scores for Yes & No
78	2	45	56	45*	11
1	26	45	52	47*	5
26	26	47	54	49	5
52	26	47	55	52	3
78	26	45	56	42*	14
1	52	52	52	48	4
26	52	49	53	51	2
52	52	47	55	54	1
78	52	45	56	38*	18
1	78	52	52	39*	17
26	78	49	53	47*	6
52	78	47	55	36*	19
78	78	45	56	37*	19

Table 13.11 The effect of changing the match and mis-match score for the question *'If the fracture surface is examined, are there any subsurface defects'* on the matching score for galvanic corrosion.

Table 13.11 shows that changing the match and mis-match weightings widely has a comparatively small effect on the position of 'galvanic corrosion' in the resultant top cases. When the question is answered 'yes', no matter what the weighting 'galvanic corrosion' is still revealed as the first choice. If the question is answered 'no', the position of galvanic corrosion is either still top or among the top nineteen cases as indicated by the * next to the figure. The majority of 'no' answers were within the top ten cases, only three had a lower position. These were for match and mis-match weightings of (78,52), (52,78), (78,78) respectively. It would be very unlikely that such extreme weightings would be used. The * in Table 13.11 indicates that the position of galvanic corrosion was superseded by Stress corrosion cracking of Stainless steel with a matching score in the range of 49 to 56 and by other failure cases where there is a low matching score, i.e. 39 and below. However, whatever the matching and answer to the question, galvanic corrosion was not totally excluded from the list of possible failure cases. This is an indication of the expert system's fuzzy logic capabilities. When the author tried to reproduce these results, the fuzzy nature of the scores was found effected by the order in which questions are asked. One question asked in a different order effected the order in which other questions were listed. Thus such a change can effect the scores and relative positions, although not considerable at the end of analysis. However, during analysis, when there are more possible failure causes and the differing scores between each failure case is narrow, then there is a greater difference (up to 6). Thus, the order and weighting of questions must be considered in any future detailed analysis of the expert system.

13.5.5 The effect of spelling errors in answering questions

Table 13.8 illustrates the effect of answering a single question with and without a single spelling error. The spelling error which was first detailed in section 13.5.2 is 'corrded' where it should be corroded. The question (*'would you considered the environment was corrosive in any way'*) was used to examine the expert system's response to the spelling error because if spelt correctly (corroded), a rule would have answered the question directly from the initial search description. Where there was a spelling error, the question was not automatically answered. Four situations were tested; whether there was a spelling mistake or not; and whether the question was answered yes or no. If the spelling was correct and the program run, the question would automatically be answered by the expert system. Thus to get a result for a correct spelling and a *'no'* answer, the question was re-examined and answered differently with a *'no'*.

Top Cases	Score with spelling error and answer question as yes	Score without Spelling error and answered question as yes	Score with spelling error and answered question as no	Score without spelling error and answered question as no	Range of scores
Galvanic Corrosion	45	47	39	41	8
Micro biological corrosion	44	45	37	37	8
Gaseous corrosion in 300 series stainless steel	40	43	39	38	5
Stress corrosion cracking in 300 series stainless steel	38	44	37	37	7
Electrostatic discharge attack on a thrust bearing	38	35	28	30	7
Cracking from precipitation of internal hydrogen, (Fish-eyes)	35	35	28	28	7
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin	33	32	29	29	4
Contact corrosion, welding with more or less noble electrode	33	34	<25	25	+8
Sulphide stress corrosion cracking in pipe lines	30	33	37	37	-7
Crevice corrosion	30	37	29	30	8
Flow erosion in pipes	30	32	38	39	-9
Hydrogen embrittlement failure of maraging steel bourdon tubes	29	30	<25	<24	+6

Top Cases	Score with spelling error and answer question as yes	Score without Spelling error and answered question as yes	Score with spelling error and answered question as no	Score without spelling error and answered question as no	Range of scores
Hydrogen induced blistering	29	29	<25	<24	+3
Pitting corrosion	29	29	<25	<24	+5
Hydrogen pressure cracking in pipe lines	28	28	34	34	-6
Stress corrosion cracking in 70% Cu, 30%	28	29	<25	<24	+5
Decarburization of steel	28	27	<25	<24	+4
Impeller failure due to repair or build up welds with pores	28	31	27	26	5
Hydrogen attack	27	28	33	33	-5
Sulphide stress corrosion cracking	27	31	26	26	5
Different cases appeared in list after this score		33	33	32	

Table 13.12 Effect of answering a single question with or without a spelling error.

The scores in Table 13.12 relate only to the current description and answered questions but clear differences and a common trend can be observed. The largest difference in scores exists for the *'yes'* answered question, with the correct spelling having the highest score. Over the range of cases the average range difference was +2 for the *'yes'* answered question, whereas for the *'no'* answered questions the average range difference was +0.166 or +1/6. The greatest differences also related to questions with a high average overall matching score. Although these differences were in some cases, large (up to 8), this was an effect felt by all cases and so the actual positioning did not completely change.

Thus the effect of a spelling error is minimal when the question is answered 'yes'. If there is a spelling error and the question is answered *'no'*, then the expert system views the description and answers as a situation that (in this case, corrosion) does not occur. This is to be expected as in an actual case there might not be an error in either spelling or answer selection and the associated cases do not relate to the investigated failure problem. However, if in the description a key word exits and this fires a rule which answers a question which (answer) is reversed by the user, the expert system does not fully accept that the condition as signalled by the keyword in the initial description does not exist. In this case, corrosion in the description answers the question as *'yes'* and the user changes this to *'no'*. This could be considered as a doubled edge sword, in that the user might have written in the

description that *'corrosion was not a problem'* and yet the expert system signals corrosion. However, it is more likely that corrosion could occur even though the user might not think that it would. In this failure case, a copper washer generally known to be resistant to corrosion, has corroded due to the galvanic action between itself and the stainless steel in a strongly alkaline solution. The users and designers did not believe that this would be a problem, and thus might have answered 'no' to the failure's association with corrosion. Thus, the fuzzy nature of the expert system allows for such errors which could not be accomplished in other pure rule base expert systems.

13.5.6 Final diagnosis.

Although the expert system previously diagnosed galvanic corrosion, further questions increase the diagnostic certainty from 47 to 66%. This is shown in the printout from the expert system given in section 13.5.7. However, this might not always be the situation. If a diagnosis was undertaken and no stored failure case directly matched the search case, then the information added to the expert system (descriptions and answered questions) could be stored to either develop a new case, or to get an accurate diagnosis, by a failure analysis human expert.

Such information is presented below as case 90 (section 13.5.6). This information also allows an analysis of the expert system's decision process by the analysis of the description, questions and suggested similar failure cases. It is observed that the expert system does not match similar cases 100%. This is typical of most investigations of complex situations. In the failure situation, there was considerable complexity by the fact that several parts and two materials were used in an aggressive dynamic environment. Yet the expert system diagnosed galvanic corrosion correctly. The most important information in the analysis was the two different metallic materials in a corrosive environment, with little signs of stress or strain. To a human expert this would be similar, but a greater significance would be given to the environmental conditions because experience would indicate that the design was satisfactory, but not in the environmental conditions with two materials with greatly differing electro-chemical potentials.

In another run by a different user using the same example, it is possible that the user will answer the questions in a different order and with different answers. Depending on the scale of these differences, a different or similar diagnosis might occur. However, as shown the expert system can produce the same diagnosis, even though there might be spelling errors and a few questions answered differently. When a question is not associated with a failure case, then it does not effect the matching score. However, when there is an association between case and question, the score will be affected, but this effect has been kept to a minimum by the repetition of question areas, the initial examination of the

description, and the different match and mis-match weightings. Thus if this analysis was run again, a few questions could be different and although the final matching score might change, the final position relative to the other cases might not. This is the advantage of this expert system's methodology compared to others.

13.5.7 Details of final printout from expert system detailing diagnosis.

The printout below, is presented in the raw format, where the only editing has been to remove extra unintelligible programming scripts. To save the whole scenario, description, questions, and similar cases, the search was saved as an unresolved diagnosis by user1, as detailed in the title. This printout could be analysed by a human expert to resolve the case.

BEGIN CASE CASE90

TITLE Unresolved Case by User1 at Thu Mar 11 02:54:02 1999

DESCRIPTION: My washer made of copper on stainless steel has corroded in sea water

QUESTIONS

What is the primary process used in manufacture. **Answer:** Machining

What primary component group is your component. **Answer:** mechanical fastenings (rivets, nuts & bolts)

Is there a source of hydrogen in the component environment. **Answer:** Yes

What is your primary material. **Answer:** Copper alloys (Brass (Zn) (Bronze, (Al,Sn,Si,ZnSi,Be,Ni,NiZn)

Would you consider the environment was corrosive in any way, . **Answer:** Yes

Does the surface look like a fatigue failure. **Answer:** No

Has the failure occurred before the part went into service. **Answer:** No

Is there extensive plastic deformation around the fracture site. **Answer:** No

Before failure was the surface in good condition, free from any initial defects. **Answer:** Yes

Does the affected area have less strength than the parent material. **Answer:** Yes

What level is the stress, (High, Low, or No load). **Answer:** No load

Is stress an important consideration in this failure. **Answer:** No

Did the failure occur at room or a higher temperature . **Answer:** Room temperature

Does a liquid flow past, through, around, or next to your component. **Answer:** Yes

Is there a liquid metal-solid metal interface (eg Hg and Cu alloy) . **Answer:** No

Has spalling or delamination of the surface occurred. **Answer:** Spalling or delamination has occurred on the surface

Are two different metals touching each other, . **Answer:** Yes

Does a gas flow around or through your component (Changed), . **Answer:** No

If the fracture surface is examined are there any subsurface defects, . **Answer:** Yes

Is the failure just surface damage or has it broken into parts, . **Answer:** Surface damage, and deformations

What is your secondary material, . **Answer:** Copper alloys

Is there any damage near to the possible fracture sites, . **Answer:** Yes

Of any stress imposed whatever level, it is steady or fluctuating, . **Answer:** Steady

Would you consider your material to be in a brittle or ductile state, . **Answer:** Ductile

Are a non-metal and a metal in contact with each other, . **Answer:** No

What are the primary environmental conditions, . **Answer:** NaCl-H2O2, NaCl Solutions, Seawater, Air , Water, Water Vapour

Are there any other possible secondary solutions in the environment, . **Answer:** NaCl-H2O2, NaCl Solutions, Seawater, Air , Water, Water Vapour

What is the secondary process used in manufacture . **Answer:** Machining

What secondary component group is your component linked to, . **Answer:** Mechanical Fastenings (Rivets, Nuts & Bolts)

Is there a covering of bacteria, fungus, or macro-organisms, . **Answer:** No

Are there any sharp corners or sharp radii, . **Answer:** No

Are two metals either in close proximity or very lightly touching, . **Answer:** Yes

What component group is NOT linked or like your component at all, . **Answer:** other

Has the component been neutron irradiated (nuclear reactors, etc). **Answer:** No

Has the component had a surface hardening treatment. **Answer:** No

Has the failure initiated within a thread run, . **Answer:** No

Does your component, have oil holes, grease nipples, etc, . **Answer:** No

Has the component been cold worked? , . **Answer:** Yes

Does your component have a keyway, . **Answer:** No

If welding electrodes are used, have they been damaged, . **Answer:** No

Are there any cracks perpendicular to the tensile stress , . **Answer:** No

If your component is a gear or shaft, does it have splines, . **Answer:** No

Has the component been electroplated, , . **Answer:** No electroplating

Has the failure occurred by a brittle or a ductile fracture, . **Answer:** Ductile

Would you consider the environmental pH to be either:, . **Answer:** High, e.g. Alkaline

Similar Cases:

(66 Galvanic corrosion)

(52 Gaseous corrosion in 300 series stainless steel)

(43 Electrostatic discharge attack on a thrust bearing)

(42 Hydrogen attack)

(41 Ductile shear face tensile fracture)

(39 Crevice corrosion)

(39 Contact corrosion, welding with more or less noble electrode)

(39 Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin)

(37 Delamination & longitudinal split in extruded aluminium alloy mast)

(37 Cracking from precipitation of internal hydrogen, (Fish-eyes))

(37 Decarburization of steel)

(36 Tensile shock overload failure on a carbon steel aircraft towing cable)

(36 External Pressure Buckling failure of pressurised vessels)

(35 Fretting fatigue)

(35 Temper embrittlements (Ductile to brittle transition type fractures))

(35 Radiation embrittlements (Ductile to brittle transition type fractures))

(35 Impact failure induced by water hammer on a welded pipe)

(33 Pitting corrosion)

(33 Caustic cracking due to poor rivetted seams in a steel ships' boiler)

(31 Ductile flat face tensile fracture)

(31 General overload failure)

(31 Excessive wear of a single sprocket or gear)

(30 Overload failure in a sand cast aluminum base alloy)

(30 General corrosion)

(30 Ductile overload)

(30 Fatigue fracture due to abrupt thread run-out)

(29 Sulphide stress corrosion cracking in pipe lines)

(28 Hydrogen embrittlement failure of maraging steel bourdon tubes)

(28 Impeller failure due to repair or built up welds with pores)

(27 Stress corrosion cracking in 300 series

stainless steel)

STATUS UNRESOLVED

END CASE

13.6 Conclusion to evaluation

Initial evaluation was undertaken be the author, by examining how unique, informative, useful, and complete the expert system was and whether the information was appropriate and all request necessary. Once developed the expert system was evaluated using a known real life failure cases. The detail given in section 13.5 show how complex the task of failure analysis is in respect to a computer rather that a human undertaking the task. Yet, the expert system was able to predict the failure mode. In other tried cases, where the actual case did not exist in the expert system's case base, failure cases similar to the failure case were predicated. This is considered a great benefit over other rule and knowledge based systems The result of the evaluation was fed back into the expert system development as an on going process.

Although this methodology was suggested by the expert system author, if a the evaluation was only undertaken by the author then the results could be bias in favour of the expert system. Thus by using someone not directly involved in failure analysis or the expert system's development, it produce an unbiased evaluation and new point of view.

Feedback from others was positive toward the expert system. Many believed the task of an expert system for failure analysis is complex and that considerable (knowledge engineering) work is involved. Many did not fully appreciate, the reasons for using case based reasoning until its abilities were explained. Feedback was requested by all from the author as to the future developments of the expert system.

Chapter 14 The use of the Internet to aid in failure analysis

14.0 Introduction

One of the major reasons for the failure of components as discussed in chapters 1 and 4 is the lack of readily available information on failure analysis. An engineer cannot be expected to know everything and thus must rely on information that is both accurate and relevant. The Internet is a rapidly developing information system (Robinson, 1996) and can, in theory, be used to provide information on failure mechanisms and failure analysis to engineers. This chapter explores the use of the Internet in failure analysis and presents a prototype engineering materials failure analysis system based on the World Wide Web.

14.1. Internet computing protocols

The Internet is the generic name for several computing protocols that run over a network of cables, satellite links, and optical fibres that link different computers together. The majority of the information in the whole Internet is based on four types of information: Promotional (Advertising), Content (news & information), Trans-actional (Banking, sales, and services), and Personal (Self-advertising). The major protocols are as follows: World Wide Web (WWW), E-mail, Internet relay chat, video conferencing, Usenet, File Transfer protocol (FTP), and Telnet.

Initially Internet relay chat enabled users to "talk" (via a keyboard) in real time to individuals or groups of people at different locations around the world. This has now developed so it is possible, by using video conferencing, that the design of an engine or the diagnosis of a patient can be discussed between professionals in real time. Any information media (text, video, audio, etc.) can be transmitted together with the simultaneous running of a programme on several computer platforms. Evaluation trials have been undertaken by companies and organisations to check the viability of such systems. For example a major engine manufacturer in England is evaluating whether such a system will allow the rectification of faults and the validation of planned maintenance to be undertaken in remote areas aided by company based engineers who have a greater skill base and easier access to company product information than found in the field (Rolls Royce Engines, 1996). By linking this system to their databases, information in the form of technical drawings and photographic images can be sent between the site of a failed component and the company's main site. This will aid in failure analysis and subsequent product information failure warning. A product information failure warning is where a company receives information related to a possible product failure from either the manufacturer or responsible group, which details the components involved, inspections methods to be employed, and remedial actions to be undertaken. Product information failure warnings are frequently used in the aircraft industry where component failure is life threatening.

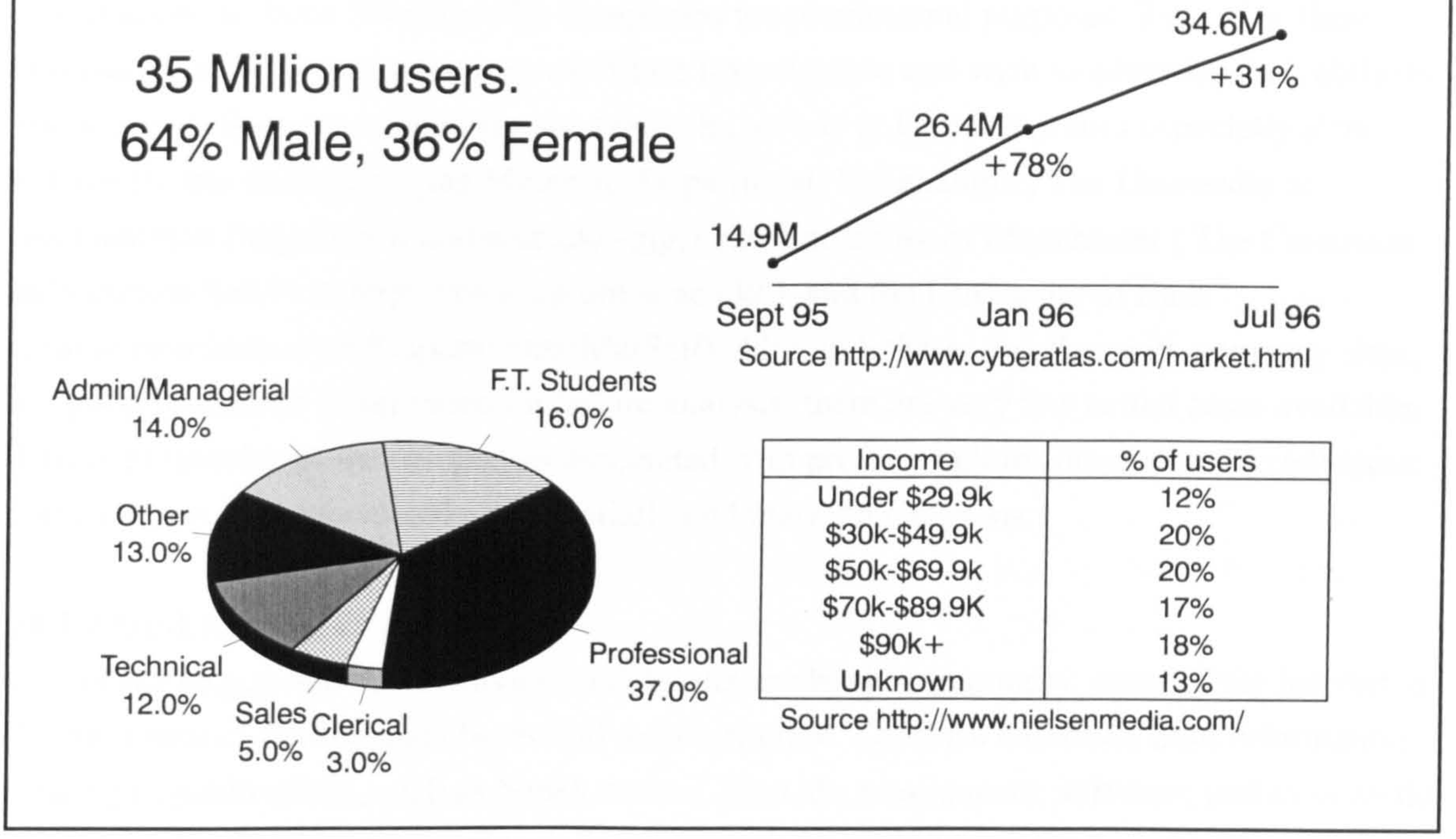
Usenet is a software based global bulletin board service that uses the Internet as an access point through different Internet hosts. It is composed of thousands of topical groupings that are made up of comments sent in via the Internet email system. These comments can either be simply read or the users can send their own comments to the topical discussion group which are made available to the whole world. The information and use of these discussion groups are similar to billboards in which questions or topical comments are posted and people respond. Although these discussion groups rely on people either making comments or replies, significant academic and commercial benefits can be gained. For example a question asking about a particular welding failure problem could be answered by a company or consultancy who could either provide a service or product which would solve the welding failure problem. Typical discussions groups include engineering safety (sci.eng.safety), engineering materials (sci.materials), and the air transport industry (misc.transport.air.industry) (Thomas, 1996).

Telnet is a standard protocol to allow one computer to access and utilize another computer. From here users could search files and gather information, if allowed, (many databases are password protected) using online archives or location searching systems, such as Gopher, Veronica, or Archie. When the information's location is found, the information can be down loaded using File Transfer Protocol (FTP), FTP being a software tool that allows users to move anything that can be stored on a computer to another computer. This is ideal for engineers working off site. (Thomas, 1996)

Of the different protocols used on the Internet, the protocol with the greatest impact, growth and user base (number of users) is the Wide World Web (WWW). The main reason is the easy of use and the simple way in which information can be represented in a graphical environment.

The World Wide Web (WWW) is a client-server software interaction that uses Hypertext Transport Protocol (HTTP) for transmitting information and Hypertext Markup Language (HTML) for formatting text, and graphic images so information can be organized and read over different computer networks, presented within web browser software applications such as Netscape. Unlike other computer languages, HTML does not describe a page with all the graphics, fonts, point size, etc., HTML only tags the content of the file with certain attributes that are later defined by the browser used to view the file. The HTML tags attributes, type styles, inserts graphics, sound and video files into text, and creates hypertext links. The hypertext links are the most important aspect within HTML. It means that any text, graphics, sound or video files can be linked together to form one document.

The next ten years will see the development of the WWW (Robinson, 1996) and the use of multi-platform programming languages, such as Java. Java is a simple form of C++, that



Income	% of users
Under $29.9k	12%
$30k-$49.9k	20%
$50k-$69.9k	20%
$70k-$89.9K	17%
$90k+	18%
Unknown	13%

Figure 14.1 Statistical Data related to the Internet.

works on any hardware platform (Hamilton, 1996). E. Yourdon (1996), states that Java will eliminate "fatware" producing a global cottage industry associated with the creation of Java components and the replacement of purchased software packages with transaction-oriented rental of Java applets attached to Web pages. (Yourdon, 1996). This means that a computer program today might in future be produced in Java, and down-loaded from the WWW and paid for in a similar manner to a video rental.

14.1.1 Growth of use of the Internet

The Internet's growth has been described in many publications and its commonly stressed with great hype, far in excess to its current abilities. However what can be seen from the statistical data shown in figure 14.1 is that the use of the Internet has doubled every year.

The largest sector using the Internet is professional men who are either using the Internet as part of their employment or have the financial resources to allow personal use from their homes. This has meant that many companies and organisations have produced information (advertisements) aimed at this target group of high earners. This in turn has further fuelled the growth of more users and the development of more information available via the Internet. However growth in usage from other sectors of the community is predicted.

The resources for failure analysis on the Internet are at present limited at best. Information on failure analysis or any topics are held at 'sites' that are locations in remote computer systems. The majority of sites are based on the World Wide Web protocol. Most of the present

information has been developed by companies for promotional purposes. Typically, these companies are working in the area of failure investigation and wish to advertise their abilities and services. Some case histories are available, mainly at University sites especially if the University has an Engineering Materials Department. For example, The University of Southampton (http://www.soton.ac.uk/~pjgj), the University of Manchester (The Corrosion Information Server at http://www.cp.umist.ac.uk/), and the University of Bath (http://www.bath.ac.uk/Departments/MatSci/). Although these, together with company sites, are good sources of information on failure analysis, there are very few actual cases available. This is in part due to the companies associated with product failures not wishing to advertise these failures for commercial confidentially and marketing reasons.

14.1.2 On-Line Search Facilities

One of the largest and most heavily used, by the academic community, areas of the Internet is the multitude of On-line data bases and search engines. On-lines databases hold information relating to publications, such as books, theses, journals, newspapers, software, and even audio -visual media. Examples of some on-line databases are as follows: CompendexPlus, WorldCat and Article 1st, BIDS (Bath Information Data Service, http://www.bids.ac.uk) BIDS ISI (Institute for Scientific Information Inc) and NISS (National Information Services and Systems, http://www.niss.ac.uk). These are of particular interest to failure analysis investigations as they can search a wide and numerous number of references.

Search engines hold information relating to the location and general content of web pages. These are extremely useful to a consultant because many organisations have produced a WWW site. However to personally hold information on each and every web site would be an impossible task, due to the extensive number of sites involved and the continuous evolving nature of web site development. Web site developers are able to submit information about their site so that it becomes accessible to search engines which check the location and list the site on their on-line data base. Examples of these are Yahoo (http://www.yahoo.com), Alta Vista (http://www.altavista.digital.com/), CUSI(searches many search sites http://Web.nexor.co.uk/susi/cusi.html), ExCite (http://www.excite.com/), InfoSeek (http://www2.infoseek.com), Lycos (http://www.lycos.com/), OpenText (http://www.opentext.com/), WebCrawler (http://webcrawler.com/), W3 Search Engine (http://cuiwww.unige.ch/meta-index.html). These public sites use anything from simple keywords to full-fledged boolean search queries. Most of these search engines work by pre-indexing and updating pointers to a vast number of Uniform Resource Locators (URLs) on the world wide web, (A URL is an emerging standard syntax for Internet resource addresses). So when users enter a search term, they are only searching a database somewhere on the Internet, not the whole actual Internet itself, which would be impossibly slow (Thomas, 1996). Thus, Web page authors have to register their pages with the public search engine before it can be

found via an on-line search. To aid in the searching techniques, Meta elements are used within the Head element of a web page to embed document information not defined by other HTML elements. Such information can be extracted by servers/clients for use in identifying, indexing and cataloguing specialised document meta-information. However, header information (Title, Meta-Text) has to be sensible, else it could be detrimental to its ability to be found and read by others. This can be solved by the web author using standard layouts and text for meta-text and using a title which describes accurately the actual web page.

14.2 Developing a knowledge-based system for failure analysis using the WWW

It is the utilisation of the hypertext facility that is useful in developing a knowledge-based system and can be employed in failure analysis by having each failure mode held on one web page. This will allow "case-based" web-searching, using the standard on-line tools. This leads to the "development by many, used by many" syndrome. In addition a simple rule based system can be used to select the different cases by using hypertext links to either other lists of other hypertext links or directly to text and graphical documents which describe different failure modes. A typical list of hypertext documents involves a question together with several possible outcomes. For example "Pick from the list below your component's material". By going through several levels of these questions, the user can find the possible failure mode. This uses the same principles as those in rule-based-reasoning knowledge-based systems, with all their intrinsic problems (Graham-Jones & Mellor, 1996). Therefore, the quality of the outcomes greatly depends on the users and their understanding of the problem. The main difference is that the information can be accessed through many different computer systems (IBM's Windows and DOS systems, Apple computers, UNIX systems) using many different browsers (Netscape, Mosaic, DOS Lynx, MacWeb, Lynx, etc.). Additionally, as HTML is very simple to write, producing a simple knowledge based system is easier, if all the information in the knowledge base is structured. The structuring of the knowledge base is an extremely complex task, especially in the domain of failure analysis. However the questioning strategy devised previously (Graham-Jones & Mellor, 1997a, and 1997b) and discussed in detail in chapter 9, is ideal to be used as the framework for the web based expert systems. The important point to make here is that the knowledge base structure developed in the development and design of the case based reasoning expert system can be used in other system, such as a multi-platform web based expert system.

14.3 Schema for the web-based failure analysis expert system.

The schema below in Table 14.1, shows a possible approach for a web based expert system. The reasoning methodology is based on rule based reason, i.e. IF x THEN Failure = y ELSE Failure = z. The links connect the table, which is on one web page, to other web pages, which give further detail on how to recognise a particular failure mode. The questions are asked in the same order that a real metallurgist might ask and they are based on work done by Renolds (1991) and Graham-Jones (1996). This idea is that an engineer with a failed component could follow the steps and gather more information which would help him conclude a possible failure mechanism. Having all the questions on one web page allows great flexibility in the approach and easy navigation through only two or a maximum of three levels of web-pages. This also means that it is easier to up-grade and obtain a print out if required. Within the present failure analysis case based reasoning expert system there are fifty questions. Great efforts have gone in development to reduce the number of questions that are required to be answered from which a diagnosis can be made. However, the programming techniques used in case based reasoning cannot be used in a web based expert system. For example, if the table below consisted of all fifty question then this would become unwieldy. Thus the first level web page details the major failure modes and leads the user on to subsequent web pages which as for more details. For example, if the fracture surface has two distinct regions and there was a fluctuating service load then a fatigue failure is proposed. The user then follows the fatigue failures link in which more information is gained and more possible questions asked. For example If the current questions had discovered the failure was by fatigue. The next question could be "Is there any corrosion evident, if yes then this would indicate ***corrosion fatigue***, Where the high lighted lettering in the words ***"corrosion fatigue"*** is a link to a web page on corrosion fatigue.

The present web pages are stored in http://www.soton.ac.uk/~pjgj however the updated web based expert system will be based in **http://www.port.ac.uk/mech/** . Details of these pages are given in the appendix 3.

Questions (IF)	**Commentary**	**Checks and links to possible failure mechanisms. (THEN) Links are given in bold italics**
What is the function of the component	What does it do? In particular, is it load bearing or highly stressed?	If load bearing then suspect ***over-load***.
What is the nature and direction of normal service loads (tension, compression, bending, shear, steady, fluctuating, cyclic, etc)	To ascertain how the component would be expected to fail under normal conditions and which cross section is critical under such loading.	Fluctuating loading means possible ***Fatigue***, where steady loading indicates possibly ***Brittle*** or ***Ductile*** fracture. ***Ductile failure*** will have some plastic deformation. ***Brittle fracture*** will have little/no plastic deformation present. If the fracture path is a helix or the fracture occurred not perpendicular to loading suspect ***torsional*** or shear failure. Torsional failure is likely to occur in shafts.
Is corrosion or wear evident?	Wastage needs to be significant but this relates to the component as there can be considerable variation in loss of original cross section to be significant on its own.	If there is dis-colouration then suspect ***corrosion***, else suspect ***wear***. However, both are possible at the same time ***Corrosion-wear***
Is there any plastic deformation? (Stretching or necking of metal, cracking of paint films, etc)	Should reveal direction of forces, which have been above the yield stress and greater than the designer intended. Most probably indicative of ***gross overload***, possibly collision forces.	Plastic deformation indicates ***ductile*** over load failures.
Are connected components in the same load transfer path deformed?	Is so, broken component must have been sound in order to be able to transmit these forces.	Check what the operator was doing at the time of failure?

Questions (IF)	Commentary	Checks and links to possible failure mechanisms. (THEN) Links are given in bold italics
Is the failure just surface damage or has it broken into parts, if so how many parts?	Parts might not fracture **(Surface damage)** or they may fracture in two parts or shatter into many parts, else they could join together	Check for the following:- Surface damage: **corrosion, pitting, discolouration, deformation, scratches, surface melting.** Two parts: **Fractures, overload, fatigue, creep** Many parts: **rupture, explosion, spalling, delamination.** Joining parts: **seized, jammed, fused**
Has the fracture path exposed any internal fault or pre-existing weakness?	Some parts, eg castings, are quite likely to contain minor internal defects. If significant, failure is likely early in life of component or fatigue starting from vicinity of defect.	Check ***Casting, Forging, Welding*** type failures and other ***Manufacturing failures***
Is the fracture uniform, or does it exhibit facets/shear lips?	Could be a brittle fracture. If component steel, was the temperature below 0°C?	If a uniform fracture then possible brittle fracture, if facets/shear lips then ***ductile failure***. Check temperature for possible ***brittle to ductile transition*** failures.
Does the fracture show a rim all round the outside?	Could be a case hardened component. File test to see if surface is hard.	Check manufacturing processes, especially any **surface treatments.** Are there any other surface cracks. Poor Cadmium plating can lead to **Hydrogen embrittlement.**
Does the fracture exhibit two or more portions of different appearance?	Suggests a two-stage fracture mechanism, which could be ***fatigue***.	Check for ***fatigue*** failures.

Questions (IF)	**Commentary**	**Checks and links to possible failure mechanisms. (THEN) Links are given in bold italics**
Are any beach or shell markings evident? If so, do they emanate from some feature on the surface which could have acted as a local stress raiser?	***Fatigue failure***. Circumstances at moment of final break of little significance. What caused the fatigue crack to initiate/propagate?	Typical causes of ***fatigue*** are ***local stress raisers, sharp corners***, small defects, ie ***welds, blunt or damaged cutting tools,***
Is there any secondary damage to the primary fracture?	Part must have been already broken.	Check use and function prior to failure. Ask operator if primary fracture was known?
Is there any rust or corrosion product on the fracture?	Could indicate a long-standing crack.	Check ***High cycle fatigue***, or check the pre-failure operation of the component.
Is there any oxidation or paint exposed by the fracture?	***Manufacturing fault***? Possible pre-existing crack.	Check for any secondary damage or fractures.
Does the fracture initiate from any sharp corners or radii	Could indicate **high stress concentrations,** thus either a poor design or a **general overload.**	Check the radius of corners and the possible loadings, and then compare with Peterson (1975).
Are there signs of heating of adjacent parts?	Was it friction or externally applied?	If frictional then possible ***seizure, frictional wear,*** or ***fretting*** problems. Else ***high temperature failures, thermal fatigue***, etc. Check for loss of coolant.
Has any recent service or adjustment been carried out which might affect the service conditions of the component?	Could have altered loading system eg over tightening of bearings	Check for ***Galling, Brinnelling, Fretting, wear***

Questions (IF)	Commentary	Checks and links to possible failure mechanisms. (THEN) Links are given in bold italics
Have any welding repairs been carried out near this component?	Accidental heat treatment can soften a high strength steel or render it brittle. Heating and cooling can cause distortion and leave residual stresses within the metal which add to the normal working loads	Check for ***welding related failure*** and check the hardness value compared with the expected value for the component.
Is the component covered by or in contact with another material.	Coverings could be liquid (water, acid, alkaline), or solid (plastic, metal, or wood)	Check for any contact between materials. Liquid:- **differential corrosion cell.** Plastic or wood: **crevice corrosion.** Metal:- **galvanic corrosion.**
Is there a covering of bacteria, fungus, or micro-organism	**Microbiological corrosion** can be found in the marine, oilfield, jet fuel, and sewage environments.	Check for biological coverings, some will require a magnifying glass other (barnacles, mussels, etc) can be seen by eye.

Table 14.1

Schema for the Web-based Expert system involving diagnostic questions, commentary, checks and ***links*** (in bold italics) to different failure mode.

14.4 Problems in developing a failure analysis WWW system

The problems of developing a failure analysis WWW system are common to all WWW systems and these can be split between technical problems and economic, social, and organisational problems. Technical problems, such as bandwidth limitations and junk information can be solved through technical development in software and hardware. Bandwidth problems are associated with the speed by which information can be transmitted. The speed has improved considerably over the last few years, though this has not been helped by the fact that much of the information on the Internet is junk, i.e. irrelevant information for your needs. Development in web searching tools, and the free on-line searching databases have greatly enhanced access to information. Another method to improve the speed is through better and simpler web page design. This means only including relevant information and not information that just improves the appearance. Complex code will reduce the cross platform compatibility and greatly increase the time to down-load information. For example, the use of Java scripts or image-maps to improve the appearance in detriment to the down-loading speed is ludicrous as it is the information which is more important (Tim Barange-Lee, Private

Communication, 1996). However the use of Java scripts can better serve the development of expert and knowledge based systems by being a cross platform programming language, which can be executed over any networked computer. This is ideal for databases but detrimental if used to cause some text to flash in multicolours.

Economic, social, and organisational problems relate to the difficulty in recouping the costs involved in producing the web pages, and who will actually provide the development? Confidentiality, correctness and relevance are other factors to consider. The organisation that actually provides the development will want to recoup its costs by marketing and promoting its failure analysis services. Educational organisations could also provide the development for educational as well as for marketing and promotional uses. Different companies from the areas of transport, insurance, and failure analysis consultancies (Open University, Personal communications, 1996), all desired such a system but could foresee problems in confidentiality and competitive advantage. The insurance and transport industries did not wish to display their failures and the consultancies did not wish to break client confidentiality, however they all wished to see relevant and up to date failure information, and this included a mix of complex and simple failure cases. The simple failures described by the different companies, were well within the reach of any diagnostic computerized system. However, if all the parties are unwilling to display their failures will the information in the system be correct and relevant? As seen in chapter 4 the present expert system is based on standard well-known failures and sanitised actual failure case histories that have had their trade name and associated identifiers removed, and hence confidentiality is maintained.

With all the technical problems, (lack of bandwidth, Junk information), development costs and confidentiality issues, actual information on failure analysis is scarce, limited and often irrelevant. Additionally, this is not helped by the fact that corroborating the information as correct and accurate is difficult. Within the more traditional publications, peer review is used in a well known and a structured manner. There is some peer review of a few Internet sites (http://www.intercorr.com/). However, this is very limited and not fully accepted by the academic community as rigorous a peer review as that which is usually associated with academic journals. This peer review problem should decrease, with increasing acceptance of on-line documentation, especially documentation from established traditional publishers.

So, more professional web sites producing accurate and relevant information are required before the Internet can be really useful to failure analysis investigations. The accessibility of different servers and file storage system presently available and the ease of programming Hyper Text Mark-up Language (HTML) means that everyone can produce web sites. However a professional site requires good design rather than clever technology. This is a mistake frequently done by developers, who add irrelevant information such as animated icons and

graphics. Irrelevant information slows the transmission of information and make the (WWW) page completely unreadable to users with physical or mental disabilities (The Royal Society for the Blind, 1997, http://www.rnbi.org.uk/).

14.5 Suggested good web site design practice

The real challenge in developing a professional web site is to focus the design towards the needs of the proposed users rather than the possibilities of technology. Any one can make a web site that is extremely visually impressive, but the main problem is that the majority of users presently have relatively slow modems with 28.8 kilo bytes per second (kbps) data transfer speeds. Data transfer speeds are unlikely to improve greatly in the near future, even thought technology is providing faster modems (33.6kbps, 56.4kbps, ISDN, & Cable modem). However the increase in network traffic (Figure 14.1) is likely to reduce the effectiveness of faster modems.

A good design should consist of the following elements :

(i) A clear, informative, and easily readable text that informs and lures visitors back. This can be achieved by making it simple and considering what is the minimum required information. If this include diagrams or photographs then use the .GIF format and keep the page below 20kb. This allows for faster loading, which is especially important for the first page. If the first page takes too long to download then users will become bored and stop downloading.

(ii) Many pages have page counters. These are fine if your page is selling a product or you wish to advertise the large number of readers of your web page. However, in most application, a page counter is irrelevant and in some cases detrimental to any public image, i.e. there is no point in showing that in the last six months the site has been visited by only seven readers.

(ii) If the web page designer wishes to have some audio or video to play when the page is opened, then the designer has to consider if it is really necessary to transmit the information required. If it is required then the designer has to have a link to a third party audio/video plug-in that might be required to actually play the clip, because there are many browsers which do not have these facilities.

(iii) When including graphical images, use small, low definition versions called thumbnails. The thumbnails appear on the web page, and if the reader wishes to see a more detailed version, the thumbnail can be selected and the full high definition version can be downloaded.

(iv) The most difficult part in web design is the structure. Most web pages start as a few pages which are added to over time. This can mean that a web site is difficult to upgrade and navigate. The best structure is when all pages are only three clicks away from the first page. This gives simpler structures, easy navigation and simpler upgrading.

(v) As most readers are using the Internet to search for information, it is highly likely that they will also wish to print out the web page. Thus, it is important that the designer takes into consideration how the web page will appear on a sheet of paper. In Europe the standard page is A4, however in America the standard page is a shorter and wider letter format. Ideally, the designer takes this into consideration.

(vi) Every few months new browsers or a new version of a browser appear. The majority of users do not use the new versions. This is for reasons such as:- difficult or unsure how to up-grade, the new browser is not the company standard, the computer will not run the new version, etc. Whatever the reason, when designing web pages it is important to make the pages equally accessible on all versions of web browsers both old & new, and graphical (Mosaic, Netscape, and Internet Explorer) and non-graphical browsers (Lynx).

(vii) Although the present expert system and web pages language is English, to include different language versions would make any computerised information system truly successful, especially so if the system is meant for the Internet. However, this poses a major knowledge elicitation problem due to the vast amount of technical translation required. Recent developments in artificial translators would ease the problem slightly, but these software translators are still limited in their abilities.

14.6 Conclusion

There are many methods available to engineers to aid them in collecting failure analysis information, but the information is presently scarce, limited, and often irrelevant. Many organisations have expressed a wish for failure analysis information to be more readily accessible through the Internet. (Open University, Private communication,1996), (Corrosion97, Private Communication, 1997)

The World Wide Web provides the best protocol for providing formatted text and images over networked multi-platform computer systems. Technical reasons for the present standard of information can be overcome by careful web page design and the introduction of new technology. However, economic, social, and organisational problems are harder to solve.

These include: recouping the costs for the developer and the quality and confidentiality of the information.

The development of an expert system based on the WWW protocol has been demonstrated. This could be developed further, by linking other computer systems together and via the use of a detailed knowledge structure. Such a structure has been developed for the case base reasoning expert system and described in chapters 4 to 8 and thus this structure could be successfully used in developing a simple prototype wed based expert system. Further development in this area would produce a multi-platform and easily accessible source of knowledge which could help reduce the propensity for some failure modes by educating engineers and designers.

Chapter 15 Data mining

15.0 Introduction

Different failure mechanisms have different probabilities of occurring. Ideally an expert system needs to take this into consideration during diagnostic decisions. A certainty factor related to the possibility of occurrence of a failure mechanism is needed.
Through the examination of different databases (data mining), very general trends and patterns in the occurrences and significance of different failure modes can be made, if the hypothesis is made that the relative number of recorded entries (hits) of a particular failure mode will indicate the approximate propensity for one particular failure mode occurring. This information can then be turned into Certainty Factors to be included within computer systems.

Data mining, also known as knowledge discovery in databases (KDD), is the process of identifying valid, novel, potentially useful and ultimately understandable patterns in data (Fayyad, 1996). It is a relatively new technique to enable the discovery of trends and predictive patterns in data that is already on-line, for the support of future decision making via the creation and testing of hypotheses and the data visualization of patterns and trends. (Mark, 1996). On-line databases are one of the most important facilities available on the Internet for published documents (books, articles, recorded information). Information is delivered in the form of titles, abstracts, references, etc. In addition to this, many can supply documents, either electronically, or via the mail. Of particular interest to failure analysis are CompendexPlus, WorldCat and Article 1st, which are available through BIDS (bids.ac.uk) and first Search (fscat.oclc.org) respectively. These on-line databases were used in the datamining analysis. Besides providing standard information, quantitative information can also be obtained on the number of recorded entries of a particular failure mode, referred to as hits.

15.1 Search results

The different data bases examined were Compendex Plus from 1978 to 1996, Compendex Ei databases from 1991 to 1996, both using a general keyword search; World Cat, using a keyword search on book title; and Article 1st, using a keyword search on article titles. These databases were selected for their relevance to general engineering, the ability to obtain numerical data from keyword searches and the free cost of these searches.

The study was performed in three stages so that the certainty factors could be assessed:-

1. Investigate the treads in time dependency of failure modes by examining six different failure modes and their records over five and seventeen years using the Compendix Ei and Compendix Plus databases respectively.
2. Investigate the trends in different databases for the same failure modes used in the first investigation. The different databases examined were Compendex Plus, Compendex Ei, World Cat, and Article 1st.

3. Investigate the trends for different failure mechanisms for fatigue and then a more detailed analysis was performed on 56 failure mechanisms as keywords to assess the actual certainty factors.

The keywords used, were either failure modes (i.e. corrosion, fatigue, deformation, creep, wear, erosion, etc.) or more detailed failure mechanisms such as galvanic corrosion, fretting fatigue. These keywords were chosen because they are considered to describe commonly occurring failure modes(Collins, 1993) (ASTM, 1986) and are representative of the wide variety of failure modes possible.

15.1.1 Time dependency

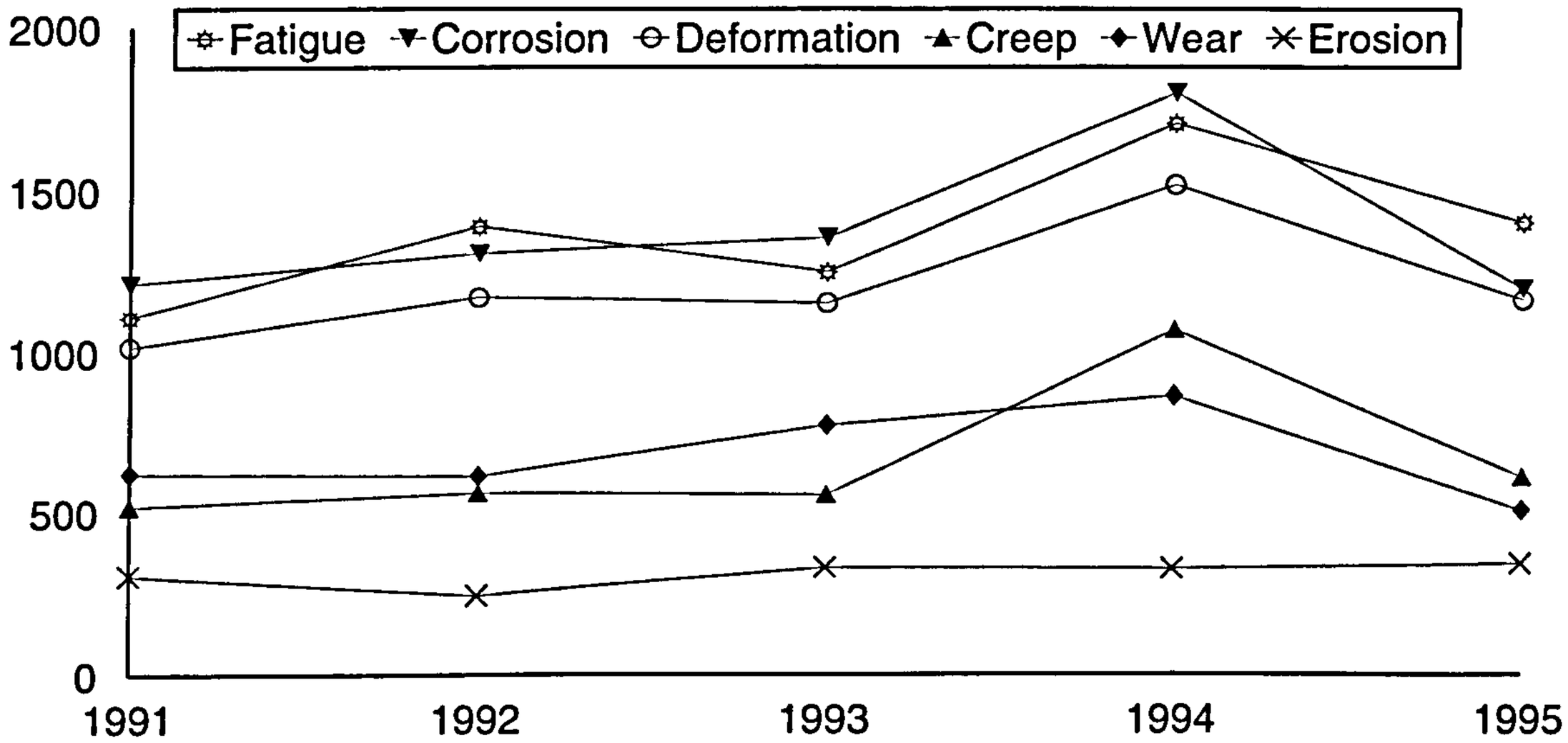


Figure 15.1. The number of hits from Compendix Ei database with respect to different principal failure modes from 1991 to 1995.

The relationship between the different failure modes and the number of hits in a database was investigated over a period of time. Initially, the Compendex Ei database was examined from 1991 to August 1996.

Figure 15.1 shows that time has an effect on the number of hits, but this effect is small in comparison to the general ranking of the different failure modes. It is also noted that an increase in the number of hits is observed during 1994 for all failure modes apart from erosion. It can be seen that the relative position (i.e. the ranking) of the failure modes for corrosion, fatigue, creep and wear changes over the years examined. This would indicate some

time dependency on ranking of the failure mode. This is also seen in Figure 15.2 which shows the number of hits from Compendix Plus for different failure modes over a 17 year period. It indicates that the range of years in which a search is undertaken is critical in assessing any trends and that over the range of years analysed there is a cyclic variation in number of hits. At present it is not clear whether this cyclic behaviour is the effect of different failure modes being in vogue, or whether it is an effect of economic trends, or even just the effect of entering more relevant data one year compared with another. However it should be noted that during 1980 and 1989, which were times of economic depression, lower hit rates were achieved for all failure modes. Furthermore, during a time of economic growth (1986) there was an increase in number of hits. Whatever the reason for this trend, its effect can be reduced by summation of hits over many years, which should mean that the most susceptible and prolific

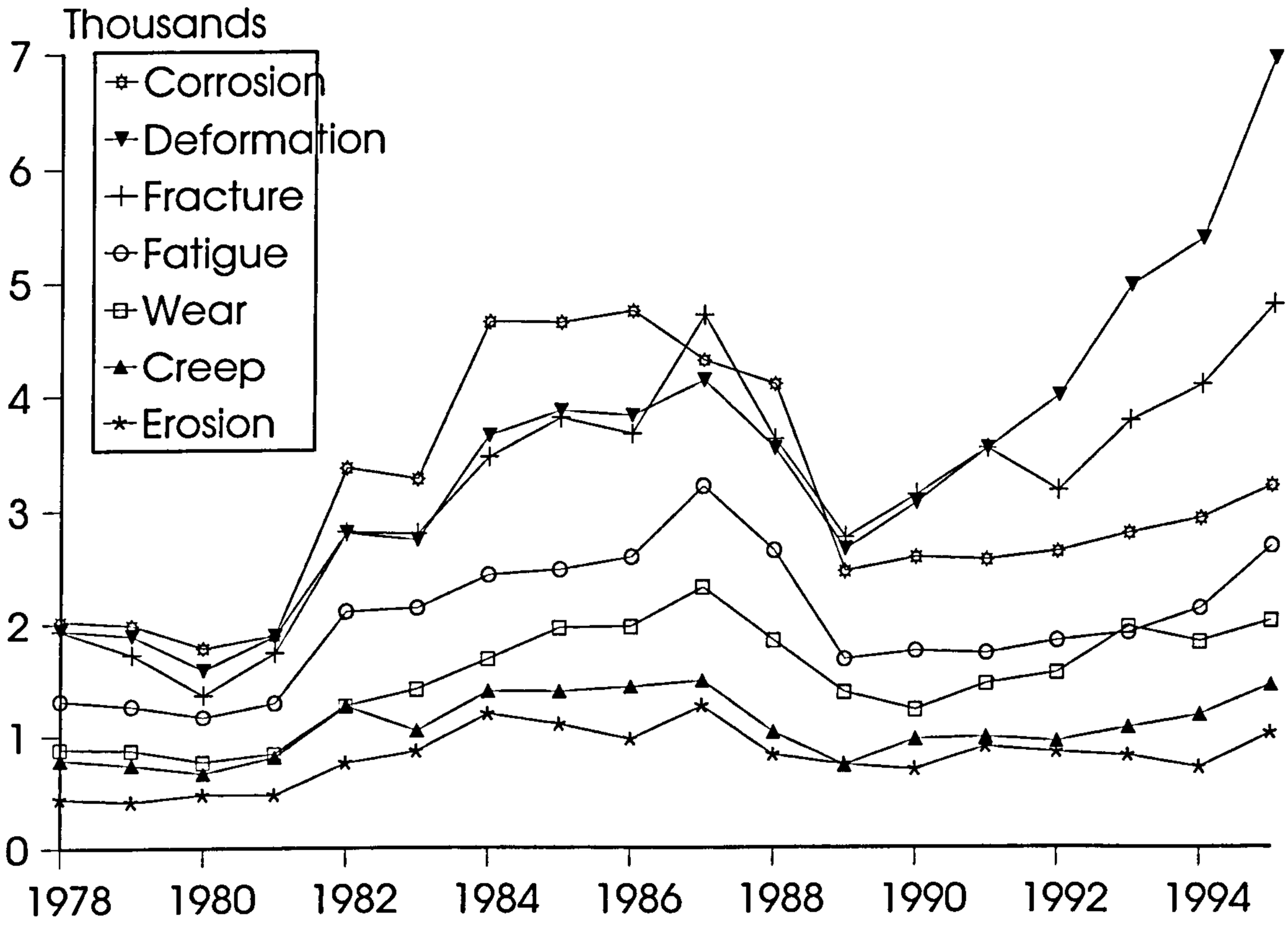


Figure 15.2. Number of hits from Compendix Plus for different failure modes over 17 years

failure modes are revealed. However, if the trend is purely a random effect due to the numbers of actual cases entered into the computer system then any trend relating to time is meaningless, unless, the actual figure of the number of entered references is taken into consideration. However this could not be done in the present case due to problems in acquiring an accurate figure for the total number of references entered for a given year.

15.1.2 Trends in different databases

The number of hits (i.e. occurrences in the database) for Corrosion and Fatigue are high as seen in Figure 15.1 and 15.2. This would be expected from practical experience, but when compared with erosion or creep, either fatigue and corrosion have been under-reported or this database is particularly skewed towards erosion failures, as much higher hits rates for fatigue and corrosion relative to erosion and creep were expected. Thus, it was important to discover differences between different databases.

Compendex Ei, Article 1st and WorldCat databases were used to evaluate any differences using the keywords: Fatigue, Corrosion, Deformation, Creep, Wear, Erosion. The time period covered was from 1991 to 1995. Their scores and the average of their scores are plotted in Figure 15.3.

Although each database had a different number of overall hits, e.g. Compendix Ei had the most and WorldCat the least, it can be observed that there is a common trend in that each failure mode has a similar relative magnitude of hits in each database. Fatigue and Corrosion had the highest number of hits compared to the other failure modes in all of the databases.

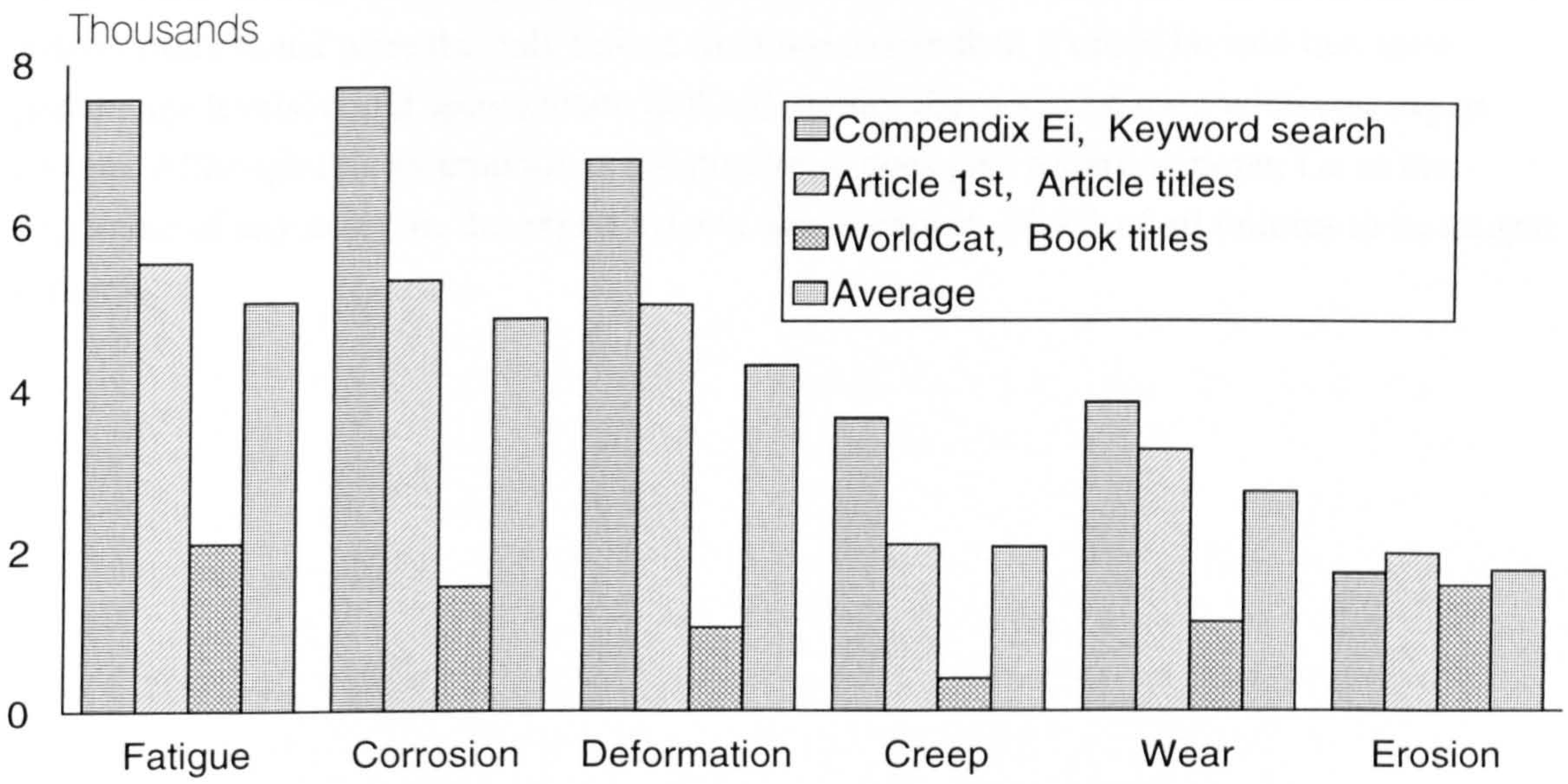


Figure 15.3. Hits form different common failure modes from different databases.

Erosion has a very similar relative number of hits in all databases. Thus, a better indication as to the relative scores was to take the average of all the database scores for each failure mode as seen in Figure 15.3. Using this value the relative average hit percentages are obtained from datamining and are detailed in Figure 15.4.

Failure Mode	Relative Hit %
Fatigue	24.4
Corrosion	23.5
Deformation	20.7
Wear	13.2
Creep	9.8
Erosion	8.4

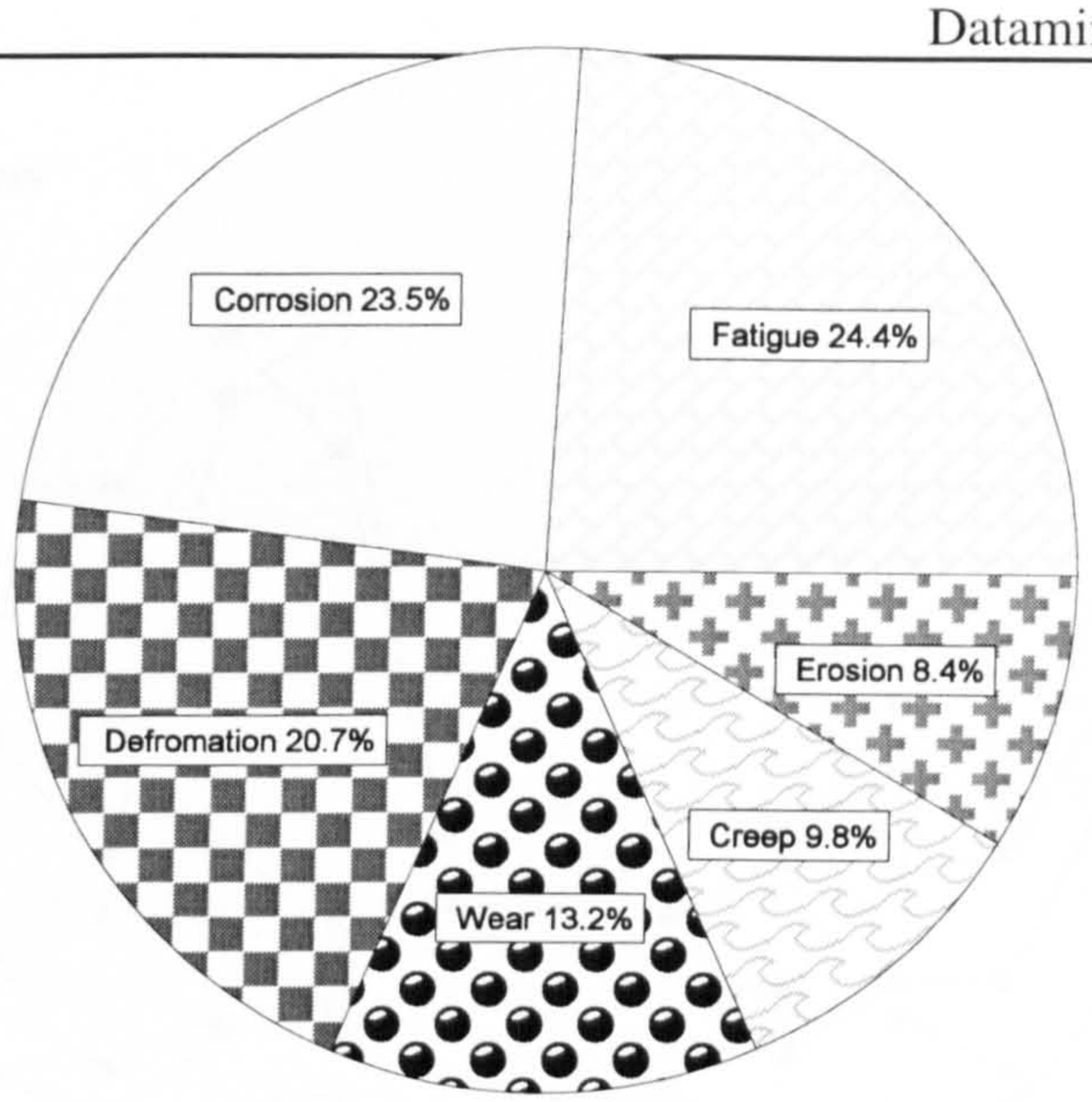


Figure 15.4. Table and chart detailing relative average percentage hits.

The relative average percentage was found by taking the average for each failure mode and dividing by the sum of all the failure mode averages and multiplying by one hundred. If it were to be assumed that the six listed failure mode were the only failure modes possible then it could be said that these percentage levels, could approximate to the Certainty Factors to be used within an expert system. Although this assumption is not precise, it does give a starting point, i.e. at the beginning of any analysis, the expert system would expect 24.4% of all failures to be fatigue failures.

15.1.3The effect of different mechanisms

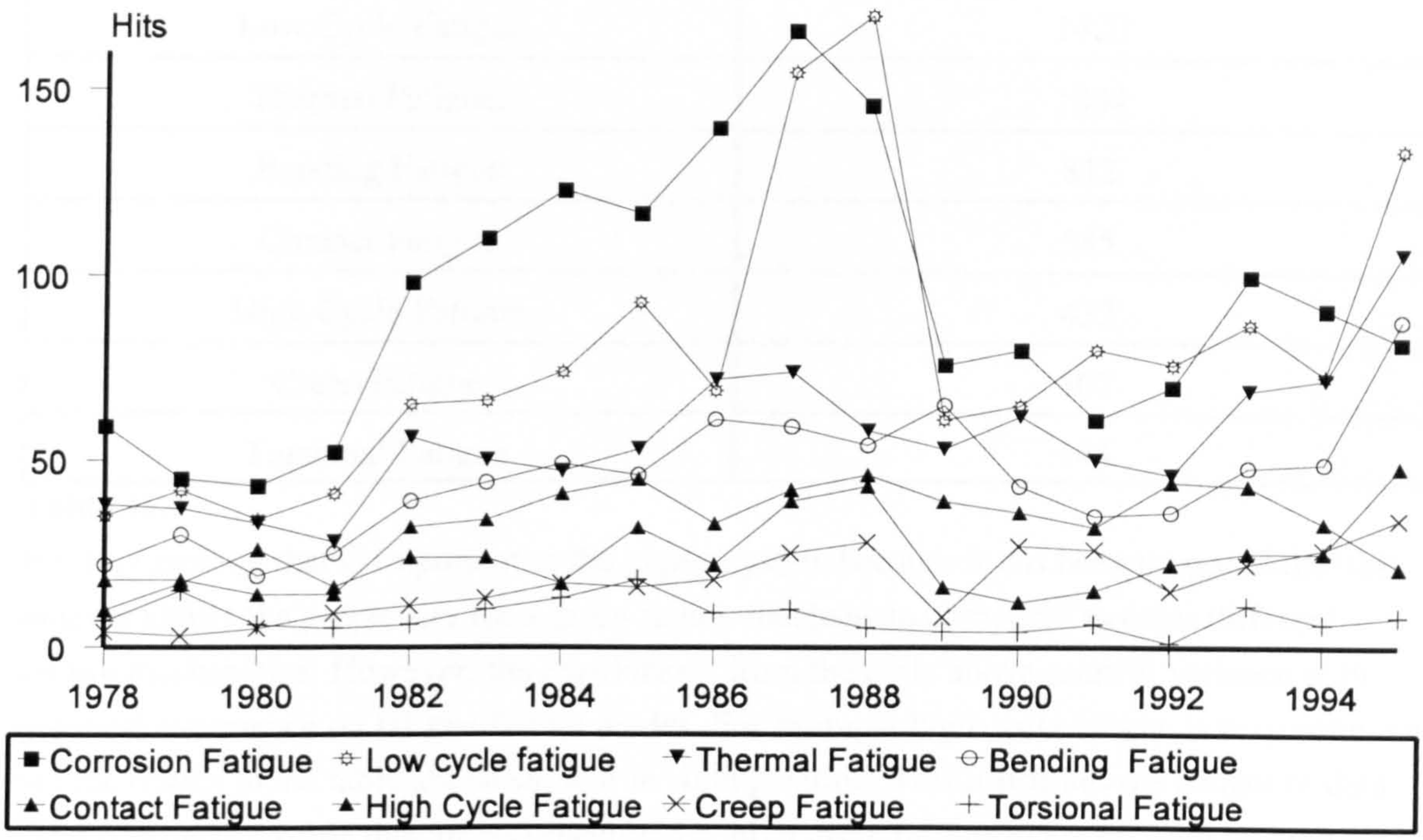


Figure 15.5. Hits scored for different fatigue mechanisms from Compendex Plus databases from 1978 to 1995.

The importance of different keywords is illustrated in Figure 15.5. This figure shows the number of hits obtained for various failure mechanisms over a 18 year period between 1978 and 1995. The relative proportion of some fatigue failure mechanisms (Corrosion fatigue, Low cycle fatigue, Thermal fatigue, and Bending fatigue) is observed to change with time whereas others (Contact fatigue, High cycle fatigue, Creep fatigue, and Torsional fatigue) do not exhibit any significant change with time. At the end of the 18 year period, all the fatigue failure mechanisms showed a general increase in hits. However it is difficult to conclude any thing as this could be the effect of more opportunities in which to publish documents of which the references are stored to produce more hits. Clearer analysis could be undertaken if the actual number of references in the database were known. However, the relative ranking position of the different fatigue failure mechanisms can clearly be observed from the table below.

Fatigue Failure Mechanism	Accumulative hits from 1987-95
Corrosion Fatigue	1659
Low Cycle Fatigue	1420
Thermal Fatigues	1004
Bending Fatigue	812
Contact Fatigue	585
High Cycle Fatigue	433
Creep Fatigue	307
Torsional Fatigue	144

Table 15.1

It is this ranking that is important to the expert system because it has been proposed that this ranking shows the propensity for a given failure mechanism compared to other different failure mechanisms. However, the conclusions from the table above seem at variance with practical experience on fatigue failure modes. For example high cycle fatigue is very common, yet the results in the table above show it in sixth position. This illustrates the danger of data mining with keywords that are too specific, i.e. high cycle fatigue when the data on high cycle fatigue is generally referred to under fatigue.

15.2 Ranking for relative occurrence.

Figure 15.1 shows the result from the Compendex Ei database from 1991 to August 1996 for different common failure modes. It was noted from the graph that there was a visible ranking. To make this visible ranking useful, summation, averaging, and normalization of the values was required. The summation of the hits for the different years as detailed in the table below, shows a ranking. This ranking indicates that the failure modes can be split into two general groups on either side of an average value of 5108 hits. Failure modes with hits greater than the average might thus be considered as more common and those below the average could be considered as less common.

Failure Mode		Number of Hits
More Common	Corrosion	7705
	Fatigue	7565
	Deformation	6801
Average		**5108**
Less Common	Creep	3645
	Wear	3390
	Erosion	1543

Table 15.2

This analysis can be extended to cover more failure modes. However, due to the extensive number of possible failure modes that could occur to a component, only the most commonly occurring failure mechanisms were used. These failure mechanisms were initially found listed in Collins, (1993) and ASTM, (1986). Table 15.3 shows the relative percentage occurrences revealed by datamining Compendix for the years from 1977 to 1997 for a given failure mechanism. The values are those which could be used as certainty factors within an expert or knowledge based system. The failure mode type indicates either a Primary (P), Associated (A), or standard failure modes without any association to a primary (F). For example deformation is a primary failure mechanism, whereas yielding and buckling are associated failure mechanisms, because deformation will occur first or be the main cause of failure. Corrosion and fatigue are primary failure mechanisms and corrosion fatigue is an associated failure mechanism of both corrosion and fatigue.

Failure Mechanism	**Failure mode type**	**No. of Hits**	**% Occurrence of primary failure mechanism**	**Rel. % Occurrence of associated failure mechanisms**
Deformation	P	73911	21.680629	-
Yielding	A	10346	-	16.649501
Buckling	A	10550	-	16.977792
Creep Buckling	A	133	-	0.2140328
Creep	P	21320	6.2538867	-
Stress Rupture	F	651	0.1909606	-
Radiation Damage	F	7161	2.1005667	-
Brinnelling	F	1	0.0002933	-
brinnel	F	4	0.0011733	-
Ductile Rupture	F	96	0.0281601	-

Failure Mechanism	Failure mode type	No. of Hits	% Occurrence of primary failure mechanism	Rel. % Occurrence of associated failure mechanisms
Brittle Fracture	F	2961	0.8685628	-
Fatigue	P	41639	12.214146	-
High cycle fatigue	A	514	-	0.8271645
Low cycle fatigue	A	1648	-	2.652076
Thermal Fatigue	A	1178	-	1.8957193
Surface fatigue	A	259	-	0.4168008
Impact Fatigue	A	180	-	0.2896685
Corrosion Fatigue	A	1845	-	2.969102
Fretting Fatigue	A	272	-	0.4377213
Creep Fatigue	A	366	-	0.5889926
Corrosion	P	62773	18.413472	-
Direct chemical Attack	A	3	-	0.0048278
Chemical Attack	F	1321	0.3874946	-
Galvanic Corrosion	A	572	-	0.9205021
Crevice Corrosion	A	1119	-	1.8007724
Pitting Corrosion	A	1691	-	2.7212745
Intergranular corrosion	A	913	-	1.469263
Selective leaching	F	96	0.0281601	-
Erosion corrosion	A	291	-	0.4682974
Cavitation Corrosion	A	504	-	0.8110718
Hydrogen damage	F	129	0.0378401	-
Hydrogen Cracking	F	528	0.1548805	-
Biological corrosion	A	25	-	0.0402317
Microbiological Corrosion	A	49	-	0.0788542
Microbiological attack	F	13	0.0038133	-
Stress Corrosion	A	7503	-	12.074348
Fretting Corrosion	A	487	-	0.7837142
Wear	P	31753	9.3142431	-
Adhesive Wear	A	422	-	0.6791117
Abrasive Wear	A	1666	-	2.6810428
Corrosion Wear	A	180	-	0.2896685
Surface Fatigue Wear	A	11	-	0.017702
Fatigue Wear	A	172	-	0.2767943
Deformation Wear	A	28	-	0.0450595
Impact Wear	A	155	-	0.2494368
Fretting Wear	A	321	-	0.5165755
Impact	P	91111	26.725979	-

Failure Mechanism	Failure mode type	No. of Hits	% Occurrence of primary failure mechanism	Rel. % Occurrence of associated failure mechanisms
Impact Fracture	A	290	-	0.4666881
Impact Deformation	A	36	-	0.0579337
Impact Fretting	A	10	-	0.0160927
Thermal Relaxation	F	332	0.097387	
Thermal Shock	F	2678	0.7855492	
Galling	F	270	0.0792003	
Seizure	F	576	0.1689605	
Seizing	F	157	0.0460535	
Spalling	F	1427	0.418588	
Totals		384647	100	70.387834

Table 15.3

The number of hits in Table 15.2 is the number of references to articles found by a search using the keywords shown in the column of the table labelled 'failure mechanism'. The percentage of occurrence is the number of hits for a given failure mechanism related to the total number of all the hits (384647) i.e. the primary(322507), associated (43739) and the normal failure mechanisms (18401), but excluding hits related to the associated failure mechanisms (43739). Thus, the percentage share relates to a total of 340908 hits. The values were calculated as follows:-

$$\%Occurence = \frac{Failure.Mode.Hits}{\sum All.the.hits - \sum associated.hits} \times 100$$

For example, fatigue is considered as a single mechanism and other mechanism of fatigue such as corrosion fatigue are excluded. The associated failure mechanisms are considered in the final column, titled Relative percentage occurrence. If these associated mechanisms are included within the initial calculations then several failure mechanisms would have a higher share than in reality. For example corrosion had 62773 hits and this is made up of many different associated failure mechanisms such as Galvanic Corrosion, Crevice Corrosion, Pitting Corrosion, Intergranular corrosion, Corrosion fatigue, Erosion corrosion, Cavitation Corrosion, Biological Corrosion, Microbiological Corrosion, Stress Corrosion, Fretting Corrosion, and Corrosion wear which together have 14767 hits. If the associated failure mechanisms hits are included with the primary failure mechanisms, corrosion, then the total number of hits are 77540 which is 20.16% of the total hits which is higher than the real percentage share for corrosion as a whole of 18.4% of the total hits. This is not correct because it assumes that the associated failure mechanism hits are in additional to the primary

failure mechanism hits, i.e. corrosion hits + associated corrosion hits. However it is correct to state that associated hits are a part of the primary hits.

Another problem dealt with in this manner is when the associated failure mechanism is a combination of several primary failure mechanisms. An example is Corrosion fatigue which is an associated mechanism both to corrosion and fatigue. Thus, splitting primary and associated failure mechanisms allows the establishment of an occurrence percentage value for corrosion fatigue, corrosion wear, impact fatigue, creep fatigue, fatigue wear, impact wear, and impact deformation to be studied. Thus the relative occurrence is calculated as follows:-

$$Rel.Occurence = \frac{Associated\,Failure\,Mechanism\,Hits}{\sum Associated + Normal\,Mechanism\,hits} \times 100$$

$$Rel.Occurence = \frac{Associated\,Failure\,Mechanism\,Hits}{62140} \times 100$$

Further observations can be observed if the failure mechanisms are ordered by number of hits.

Failure Mechanism	Failure mode type	No. of Hits	Hits divided by 17 years
Impact	P	91111	4556
Deformation	P	73911	3696
Corrosion	P	62773	3139
Fatigue	P	41639	2082
Wear	P	31753	1588
Creep	P	21320	1066
Buckling	A	10550	528
Yielding	A	10346	517
Stress Corrosion	A	7503	375
Radiation Damage	F	7161	358
Brittle Fracture	F	2961	148
Thermal Shock	F	2678	134
Corrosion Fatigue	A	1845	92
Pitting Corrosion	A	1691	85
Abrasive Wear	A	1666	83
Low cycle fatigue	A	1648	82
Spalling	F	1427	71

Failure Mechanism	Failure mode type	No. of Hits	Hits divided by 17 years
Chemical Attack	F	1321	66
Thermal Fatigue	A	1178	59
Crevice Corrosion	A	1119	56
Intergranular corrosion	A	913	46
Stress Rupture	F	651	33
Seizure	F	576	29
Galvanic Corrosion	A	572	29
Hydrogen Cracking	F	528	26
High cycle fatigue	A	514	26
Cavitation Corrosion	A	504	25
Fretting Corrosion	A	487	24
Adhesive Wear	A	422	21
Creep Fatigue	A	366	18
Thermal Relaxation	F	332	17
Fretting Wear	A	321	16
Erosion Corrosion		291	15
Impact Fracture	A	290	15
Fretting Fatigue	A	272	14
Galling	F	270	14
Surface Fatigue	A	259	13
Impact Fatigue	A	180	9
Corrosion Wear	A	180	9
Fatigue Wear	A	172	9
Seizing	F	157	8
Impact Wear	A	155	8
Creep Buckling	A	133	7
Hydrogen Damage	F	129	6
Ductile Rupture	F	96	5
Selective Leaching	F	96	5
Microbiological Corrosion	A	49	2
Impact Deformation	A	36	2
Deformation Wear	A	28	1
Biological Corrosion	A	25	1
Microbiological Attack	F	13	>1
Surface Fatigue Wear	A	11	>1
Impact Fretting	A	10	>1
Brinnel	F	4	>1

Failure Mechanism	Failure mode type	No. of Hits	Hits divided by 17 years
Direct chemical Attack	A	3	>1
Brinnelling	F	1	>1
		384647	
Totals		310736	

Table 15.4

In examining the data in Table 15.4 it can be observed that the actual number of hits can be banded into groups. The banding is very arbitrary and depends on the observer. However, from the data above the following bands given in Table 15.5 are suggested

Description	Approximate Banding for Number of Hits*	Approximate Banding for Normalised hits per year over 20 or 17 years	
		20 years	17 years
Highly Occurring	Above 3000 Hits (150)	Above 150 Hits per year	Above 175 Hits per year
Common	Between 3000 and 900 (45) Hits	Between 150 and 45 Hits per year	Between 175 and 50 Hits per year
Less Common	Below 900 and above 90 (4.5) Hits	Below 45 and above 5 Hits per year	Below 50 and above 6 Hits per year
Minimal Occurrence	Below 90 Hits	Below 5 per year	Below 6 per year

Table 15.5 * Hits from Compendix from 1977 to 1997.

The banding figures used are simplified, i.e. rather than use 4.5, a figure of 5 was used. The actual band values will change in accordance with the actual number of years, and thus the figures have been normalised by dividing the actual number of hits by the number of years in which the data was collected. Thus the figure of twenty was used. However, if the data is to be used to access the current or future probability of occurrence of a failure mode, it must be realised that these are average values and as there were few actual hits in 1977 to 1980 and many more hits in the mid to late 1990's, (as seen in figure 15.6) it could be suggested that a lower figure of around 17 rather than 20 should be used as the divisor. This might give a better appreciation of current normalised values. If 17 is used the bands would be at 175, 50 and 6 hits per year.

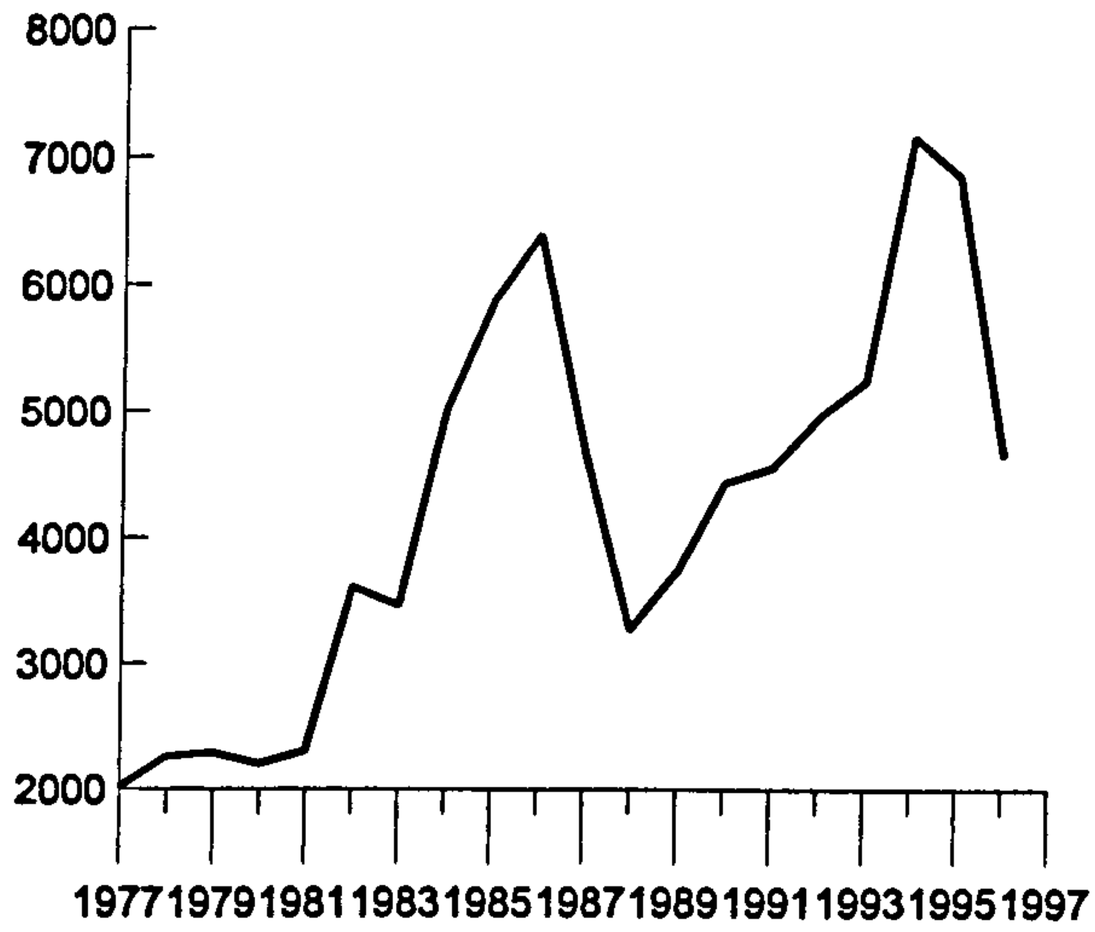


Figure 15.6 Total number of hits per year for primary failure modes.

This information could be developed into an Expert system question as follows:

Question:-

"What is your estimate of the occurrence of this type of failure?"

Answer:-

Very highly occurring.

Highly occurring.

Minimal occurrence.

Very minimal occurrence.

Note however the actual values are not used because they relate to a database of 310,736 hits. A human operator could only make subjective estimates to the occurrence of a particular failure situation compared to other known situations.

Also this banding could be used to affect the matching scores in the expert system for different failure cases in a similar but more simpler manner than that of actual percentages. Due to the fuzzy nature of the results of datamining, this might give more consistent results.

15.3 Discussion on the problems with data mining the online databases of published documents

Searches of the online databases of published documents only give a statistical indication of the number of publications on a given failure mode, rather than the actual number of reported failures. However, this is sufficient to give general trends in the relative weighting used for failure mechanisms in a computer system. For example, if there has been a disaster involving many deaths such as that of the Comet air crash, lots of interest will be expressed in the field of fatigue. This will produce many reported publications even though there were only a few failures. If the range of years used in datamining are concentrated around the disaster then an unrealistically high certainty factor will result. However if the hits are averaged over time, they should give a more realistic indication of the relative importance of different failure mechanisms. However as the data only refers to reported failures, many simple and expected failures go unreported. For example, corrosion in a car is expected and hence goes unreported. Thus the certainty factors calculated will underestimate the more simple and expected failure types e.g. fatigue, wear, corrosion, in favour of more exotic failures which are reported. Is this ideal? This would depend on what is wanted from an expert or knowledge based system for failure analysis. If the users were highly skilled consultants, it is unlikely that they would need to look up simple types of failures. Therefore, the users would prefer the system to be based on exotic failures. However if the users were either students or newly trained engineers, they would prefer the expert system based on failure modes which have the greatest occurrence.

This problem is dealt with by examining the occurrence of failure mechanism references over the largest range of years possible, i.e. When using Compendix to calculate the certainty factors, the maximum range of years possible (1977 to 1997) was used. Some of the other databases only covered a smaller range of years. These could still be included in calculating the significance of failure modes. However, integrating the results of two or more databases could mean that some references are referred to in both or several databases and thus give an increased score. It could be argued that this was both good and bad for the analysis. It could indicate that this type of failure was of great importance and thus useful. Else it could simply indicate that a particular journal's references were included in both. Whatever the reason it would still indicate a scale of interest albeit somewhat difficult to judge and thus requiring further investigation.

Another problem is that the words used in searching through the different databases could have non-engineering meanings. For example Fatigue -> Human fatigue, Erosion -> Geology erosion. This is more likely to be a problem when using general English terms. From Table 15.3, a higher possible error must be considered for the following failure mechanisms:- fatigue, deformation, yielding, buckling creep, wear, impact, seizure and seizing. These, and possibly others, depending on the sources of data, could cause a far higher hit rate than is

actually related to the failure mode. However by only using real engineering databases i.e. Compendix rather than some mixed subject databases i.e. Institute for Scientific Information (ISI), many of these non-engineering references are not present.

Another method to reduce this problem, is the use of word combinations that reduce the possibility of the search being linked to non engineering failure meanings. Form Table 15.3 the effectiveness of this method can be seen by the reduced number of hits associated with these word combinations. For example, Wear = 31753 hits; Impact = 91111 hits; Impact wear = 151 hits. With these results in mind it could be argued that the general words used in the searches should be excluded from the results. However, this would assume that general failure modes do not occur on their own. This might be true at the microscopic scale. However, general failure modes are described singularly, rather then in combination with other failure terms. For example "Automobile Corrosion Due To Road Salt" (Baboian, 1981). Further work could be undertaken to include other engineering terms that could be used in combination with the general failure modes, but would not themselves be terms used as failure mechanisms. Typical combinations would have to be linked with the logical OR so that a database search could be undertaken. For example for one hit the following condition must be true:- Fatigue OR cars OR trains OR transportation OR vehicle OR automobiles OR tractors OR bicycles OR ships OR etc. The only problem with this is that the list of words required to cover all possible engineering situations would be extremely extensive and it is unlikely that the list would be complete and cover all possibilities. Also by using the logical NOT in combination with the general failure mode words and the logical OR linked words, an increased accuracy would be possible. The logical NOT would take out references i.e. hits, whereas logical OR would add references. Examples of logical NOT words are as follows:- financial, social, ecological, political *(impact).* However, this is not as easy as it first seems, because there could have been a financial, social, ecological, or political *impact* due to a failure, similar to the failure at the three-mile Island nuclear plant, or the Exon Valdes in Alaska. Therefore, although the methods of combining or excluding words from a search could possibly bring more consistent results, unless done in a very extensive manner covering all possibilities, it could lead to even less consistent results than we presently have in Table 15.3 The use of combining actual failure mechanisms together for searches does however improve the accuracy.

Another method to reduce the problem of unrelated hits being taken into consideration would be to examine all the references, but considering the total number of references involved, 384647, this would be a considerable task both in time and expense, and thus not practical.

It has been shown that bands of relative occurrence could be directly used within the expert system rather than using the method of exact percentage of relative occurrence. This is due to

the general fuzzy nature of the datamined search results. Further investigations are required in this area before any firm conclusions are made, this could be via a survey (chapter 16).

15.4 Future work

To improve the certainty factors reliability still further would require the analysis to be extended to cover more failure modes and more databases. This might involve all the different failure mechanisms possible which would be a considerable task. However this might not be necessary, if the diagnosis does not require analysis of all the different failure mechanisms. This is observed in Table 15.4 where the occurrence of certain failure mechanisms was found to be below 1 hit per year. These could be excluded from the search, which would, in turn, simplify the whole expert system although this might not by wanted be an expert in failure analysis who might require the exotic failure in an expert system. Further investigation into the effects of banding on failure analysis searches should be undertaken.

15.5 Conclusion on Datamining

Through data-mining quantitative information on failure modes and mechanisms exists. The amount of information varies with search location, i.e. the databases used, range of years involved in the search, and the economic climate. The use of this information to aid failure analysis has been demonstrated by producing estimated percentage values for the occurrence of different failure mechanisms. Although there are some doubts as to the accuracy of these values, the initial results are promising enough to merit further investigations to improve their accuracy. These investigations could be via the examination of several other databases, with special interest being placed on the number of actual inputted records, and the semantics and different methodologies by which failure mechanism are described. Also further analysis of the number of references in these databases to either give a percentage or a level of occurrence has proved very promising, and should lead to more consistent questions and answers which would improve the accuracy of the failure analysis expert system.

Chapter 16 Survey of possible users

16.0 Introduction

A survey was developed to help answer three fundamental problems in expert system development. These were:-

1) What was the computing ability of the users? This included what confidence they felt in their ability to use computers.

2) What was their understanding of failure analysis and different failure mechanisms? This includes their experiences and how confident they felt about recognising different failure mechanisms.

3) What were their needs for a computer system that would aid any failure analysis they might undertake?

The survey was important because the outcome from these questions would influence the level of information given in user instructions, and on failure analysis and mechanisms. For example if the users had a high computing ability, less time and resources would go into developing instructions and more time and resources would go into providing failure information. What detail to include in failure information was answered by the second and third questions above. If the user had a good understanding of failure mechanisms, then an advanced treatment of failure mechanisms would be required. However, if a user was new to the field, greater background information would probably be required. As many users will have different educational backgrounds, it is likely that they will not know all types of failure mechanisms. Hence questions on different failure mechanisms are posed.

16.1 Survey design and methodology

The survey shown in section 16.1.2 is four pages long. The first page differentiated the users' responses from each other by their personal details (name, address, telephone, fax and email) and gathers information as to their academic qualifications, working experience, and their approximate age. The personal contact details were asked in case the author did not understand responses and thus could seek clarification. However, it was made optional and assurances were given in an initial statement, as follows:-

> *This questionnaire is for academic research purposes only and will not be used as a marketing tool. Personal details are optional, but adding your personal details would allow the researchers to give you feedback. Both positive and negative comments are welcome.*

Some surveys were posted or handed out to possible users. This allowed for the broadest circulation of surveys and thus a return address, fax and email were included on all separate pages, in case a page was missing or the address was damaged in transit.

The second page asked for users' feelings on computers and how they personally use them. Their responses were split into very confident, confident, some confidence, little confidence, no confidence, by means of a tick in a corresponding box. The questions start by asking very general computer problems before asking questions directly related to the feelings on expert and knowledge based systems. This was done to gauge the uses' responses against other known computer packages.

The third page contained questions related to their understanding and experiences of failure analysis, and how confident they were in recognising different failure modes. The different failure mechanisms were in five sections; commonly occurring failure mechanisms, less commonly occurring failure mechanisms, processing failures, component failures, and material failures. The purpose was to compare their responses and find common areas in missing knowledge. The responses were the same as page 2, i.e. very confident to no confidence and required a tick in the table. An additional column was added in which users were expected to estimate the likely percentage expected occurrence of a failure mode. For example it is a common belief that some percentage value can be assigned to the occurrence of failure mechanisms such as fatigue. These quoted values generally are due to personal interpretations of an engineer's own experience. In the authors own experience around 25% (one in four failures) of all general failures and 80% of all fractures are due to fatigue, although there is no defined scientific backing to these figures and thus they are considered very inaccurate. However, how true this belief is among engineers and what percentage level they assign to different failure mechanisms was hoped to be tested. Details were given both verbally and written on how to complete this column. The written details asked for the "% Expected occurrence, i.e. 1:20 or 1:10 etc." and a further note stating "The percentage expected occurrence relates to your experience. For example, if there are 100 random failures what percentage would be expected to have failed by a given failure mode. Remember the figures do not have to sum to 100% as there are only a few mechanisms detailed above and these could be combined failures". With these figures it was hoped to assess the relative likelihood of one failure mode against another and this information could be compared against the failure mechanisms relative occurrence in on-line databases. This relative occurrence data could than be used to aid diagnosis of failure cases. For example, all factors being equal, fatigue was more likely to occur than hydrogen cracking. However, respondents had great difficulty in undertaking this task and most left this column blank as they said that the task was too difficult and they were unwilling/unable to make an educational estimate. Thus, the results from this column are not presented.

The final page, (page four) asked the users for their needs as to a computer system to aid them undertaking failure analysis. Questions asked the users for their experience in failure analysis, and whether they wanted an educational or professional tool. This was backed up by other questions asking if the required information should be fully explained and unambiguous with many details or highly professional with complex terms. Also questions asked how long should the analysis take and whether a quick answer would be satisfactory.

The survey design has undergone many minor design changes to make the survey easier and intuitive to use. Examples include the following:

(1) Changing Industrial experience to working experience, as many academics believed that this meant time spent in industry rather than academic work in a university.
(2) The inclusion of post/zip code and email address for safer posting and easier feedback.
(3) MSc and PhD to Master and Doctorate to cover different abbreviations (e.g. MA, MPhil, DPhil).
(4) Asking a general question about knowledge based and expert systems before asking about failure analysis expert systems, as in page 2.
(5) Simplification of terms, such as on page 3: "A fatigue failure" to "fatigue" or "an analysis of a corroded product" to "corrosion". This makes it less confusing to users and means fewer different interpretations of the terms as there are fewer words.

16.1.1 The respondents

The survey was given to two main groups of respondents, (I) professional engineers and (ii) young and student engineers undertaking doctorates in engineering. These two groups were asked as it was felt that the expert system would be used both by professional engineers undertaking a real failure investigation, or analysing a new design against possible failures and by students as an educational tool either in a laboratory or private study.

The study was kept to respondents with some connection either academically or practically to failure analysis. Targeting the survey at such a specialised group had the advantage that these respondents were the likely users of the software. However, it did mean that the number of respondents was lower than ideal, this being 24.

16.2 Questionnaire on the development of an expert system for failure analysis

Questionnaire *This questionnaire is for academic research purposes only and will not be used as a marketing tool. Personal details are optional, but adding your personal details would allow the researchers to give you feedback. Both positive and negative comments are welcome.*

Name : _____

Company: _____

Address: _____

_____

_____

Post/Zip code:-_____

Email:_____

Fax:_____ Tel:_____

Please tick all that apply

Academic Qualifications		**Working Experience (years)**		**Age group**	
O Levels/GCSE		None		Up to 22	
BTEC OND/C		0 to 1.5		Up to 29	
A-levels		1.5 to 3		Up to 39	
BTEC HND/C		4 to 7		Up to 49	
Degree		8 to 10		Up to 59	
Master		11 to 20		Up to 69	
Doctorate		21 & Over		Over 70	

Occupation : _____

Industrial sector (Please pick ONE only)

Academic, Manufacturing, Consultancy, Government, Maintenance, Design, Research Establishment.

Others _____

Specialist Academic/Industrial Interest : _____

_____

_____

Please read the statements below and tick the box which most closely matches your feelings.

Please add any other comments in the space below the table.

Question Related to your feelings of Computers and how you personally use them	Very Confident	Confident	Some confidence	little confidence	No confidence
How confident do you feel about using a computer?					
How confident do you feel about using a word processing package e.g. WordPerfect, MSWord					
How confident do you feel about using a database system eg Paradox, Dbase, Access					
How confident do you feel about using a spreadsheet package eg Quattro Pro, Excel					
How confident do you feel about using a programming language eg C++, Visual Basic					
How confident do you feel about using a technical drawing package e.g. AutoCAD					
How confident do you feel about using the Internet to search and retrieve information					
How confident do you feel about using a knowledge based or expert system					
How confident do you feel about using an expert system to aid failure analysis					

Any Other Comments

Please return to: Jasper Graham-Jones, Engineering Materials, Southampton University, Southampton, Hampshire, England, U.K. SO17 1BJ or fax +44 1703 593016.

Question Related to **your understanding** and **experiences** of Failure Analysis. How confident do you feel about undertaking an analysis on the following failures listed below	Very Confident	Confident	Some confidence	Little confidence	No confidence	%Expected occurrence, i.e. 1:20 or 1:10 etc.
corrosion						
fatigue						
stress corrosion failure						
creep						
deformation						
erosion						
wear						
A **ductile** fracture						
A **brittle** fracture						
temper embrittlement failure						
radiation embrittlement failure						
impact or shock loading failure						
embrittlement by liquid metal failure						
Hydrogen damage failure						
caustic embrittlement failure						
sour-gas environment failure						
welding failure						
forging failure						
casting failure						
gear failure						
bearing failure						
spring failure						
lifting equipment failure						
tools and dies types of failure						
A **polymer/plastic** failure						
A **polymer composite** failure						
A **glass/ceramic** failure						
A **non-ferrous material** failure						
A **ferrous material** failure						

Any Other Comments

The percentage expected occurrence relates to your experience. For example, if you were given 100 random failures what percentage would you expect to have failed by a given failure mode. Remember the figures do not have to equal 100% as there are only a few mechanisms detailed above and these could be combined failures.

Please return to: Jasper Graham-Jones, Engineering Materials, Southampton University, Southampton, Hampshire, England, U.K. SO17 1BJ or fax +44 1703 593016.

Question Related to your needs for a computer system to aid you in undertaking failure analysis as described above	Strongly Agree	Agree	No Comment	Disagree	Strongly Disagree
I carry out failure analysis often					
Engineering failure analysis is easy to do					
An expert system for failure analysis is a good idea					
To produce an expert system for failure analysis is a difficult undertaking					
An expert system for failure analysis would be useful for me in general					
An expert system for failure analysis would be useful as a professional tool					
An expert system for failure analysis would be useful as an educational tool					
An expert system for failure analysis would be useful if all the terms were explained in a fully detailed and unambiguous manner					
I require information in an expert system that is at a high professional level (not too simple).					
I require information in an expert system to have a reference rather than an extensive and detailed description for the failure mode.					
I require extensive photographs within an expert system.					
A quick and easy to use expert system is very important					
If the analysis takes longer than three minutes, I would be reluctant to use the expert system.					
A definition of a failure relates to a person's perception and experience					
I undertake failure analysis in many fields, e.g. shipping, aerospace, domestic white goods, oil					
I undertake failure analysis with many material types, e.g. glass/ceramic, polymer, metals					
Generally I undertake failure analysis with metals					

16. 3 Survey results

Although it was wished to differentiate the views of professional and young engineers, the numbers surveyed (24) was too small to make clear difference in all questions. Thus, many responses between professionals and young engineers were combined. However, to have a clear representation of the general engineering profession, a broad covering of all age groups and different lengths of industrial experience was obtained. This is shown in table 16.1.

Academic qualifications		**Working Experience (years)**	Responses	**Age group**	Response
O levels/GCSE	16*	None	0	18 to 22	3
BTEC OND/C	4*	0 to 1.5	5	20 to 29	8
A levels	15*	1.5 to 3	3	30 to 39	4
BTEC HND	2*	4 to 7	7	40 to 49	2
Degree	19*	8 to 10	2	50 to 59	3
Master	10	11 to 20	1	60 to 69	0
Doctorate	10	21 & Over	4	70 and over	0

Table 16.1

The responses from the academic qualifications were inconclusive as many respondents did not include all of their lowest qualifications (indicated by * in table 16.1) although they might have completed a higher qualification. Of those who did the majority had O Level/GCSE, A levels and a degree, only two were undergraduate degree students and BTEC qualifications were under represented. Although understanding the respondents educational background is interesting in that it shows their experience and career path, in undertaking this survey again only the highest academic qualification will be asked.

Thought out the survey the total number of responses in each category were summed and converted to a percentage by dividing by the total number of responses to that question. Thus all questions on page 2 relating to computers and how the user felt about them were combined and normalised and compared against questions relating to expert and knowledge based systems. The results are shown below in table 16.2 and can be summarized by saying that most users are very confident about using computers. However, they are only confident about using a knowledge based or expert system and only have some confidence about using an expert system to aid analysis of situations such as engineering failures. These values are generally what was expected from this group of engineers which were generally computer

literate. It has implications about where some engineers would use the expert system due to their preconceived lack of confidence in expert system for failure analysis. However the results showed the respondents were overall confident in using computer. This is important for any computers based solution.

User feelings	Very confident	Confident	Some confidence	Little confidence	No confidence
Computers in general	**36.84%**	34.5%	13.45%	9.36%	5.85%
Using a knowledge based or expert system	8.7%	**43.48%**	30.43%	13.04%	4.35%
Using an expert system to aid analysis of situations such as engineering failures	8.7%	21.74%	**47.83%**	17.39%	4.35%

Table 16.2

In a similar manner to the questions relating to computing on page two of the survey, questions on page three relating to the respondents understanding of different failure modes were combined into groups and the percentages were calculated and the results are presented in Table 16.3.

Confidence in recognising failure mechanisms.	Very confident	Confident	Some confidence	Little confidence	No confidence
corrosion, fatigue, stress corrosion failure, creep, deformation, erosion, wear, ductile and brittle fractures	25.98%	**37.75%**	24.51%	8.33%	3.43%
temper, radiation, caustic and liquid metal embrittlements, impact or shock loading, Hydrogen damage, sour-gas failures	7.55%	12.58%	23.90%	**30.82%**	25.15%
welding, forging, casting	11.76%	**38.24%**	26.47%	17.65%	5.88%
gears, bearing, spring, lifting equipment, tools and dies	17.43%	26.61%	**33.94%**	14.68%	7.34%
polymer/plastic, composite, glass/ceramic, ferrous and non ferrous materials	14.04%	**41.23%**	24.55%	10.53%	9.65%
All stated failure mechanisms	16.62%	**30.00%**	26.3%	16.3%	10.77%

Table 16.3

Table 16.3 shows that respondents have little confidence in recognising temper, radiation, caustic and liquid metal embrittlements, impact or shock loading, hydrogen damage, and sour-gas failure mechanisms. These failure mechanisms are generally less common than the other stated failure mechanisms. Also respondents only have some confidence in recognising failure mechanisms related to gears, bearings, springs, lifting equipment, tools and dies, i.e. products or components. As respondents have difficult in recognising less common and component related failure mechanisms, (table 16.3) does this mean that the expert system should be based on these failure modes as it is likely that these will give most engineers more problems? However, the common failure mechanisms are causing more failures than less common mechanisms and are thus a greater problem that could require the assistance of an expert system for failure analysis. Further investigation of the issues is required.

Confidence in recognising all stated failure mechanisms.	Very confident	Confident	Some confidence	Little confidence	No confidence
Professional Engineers	17.10%	**38.84%**	27.84%	12.76%	3.48%
Young engineers	16.07%	20.00%	**24.59%**	20.33%	19.08%

Table 16.4

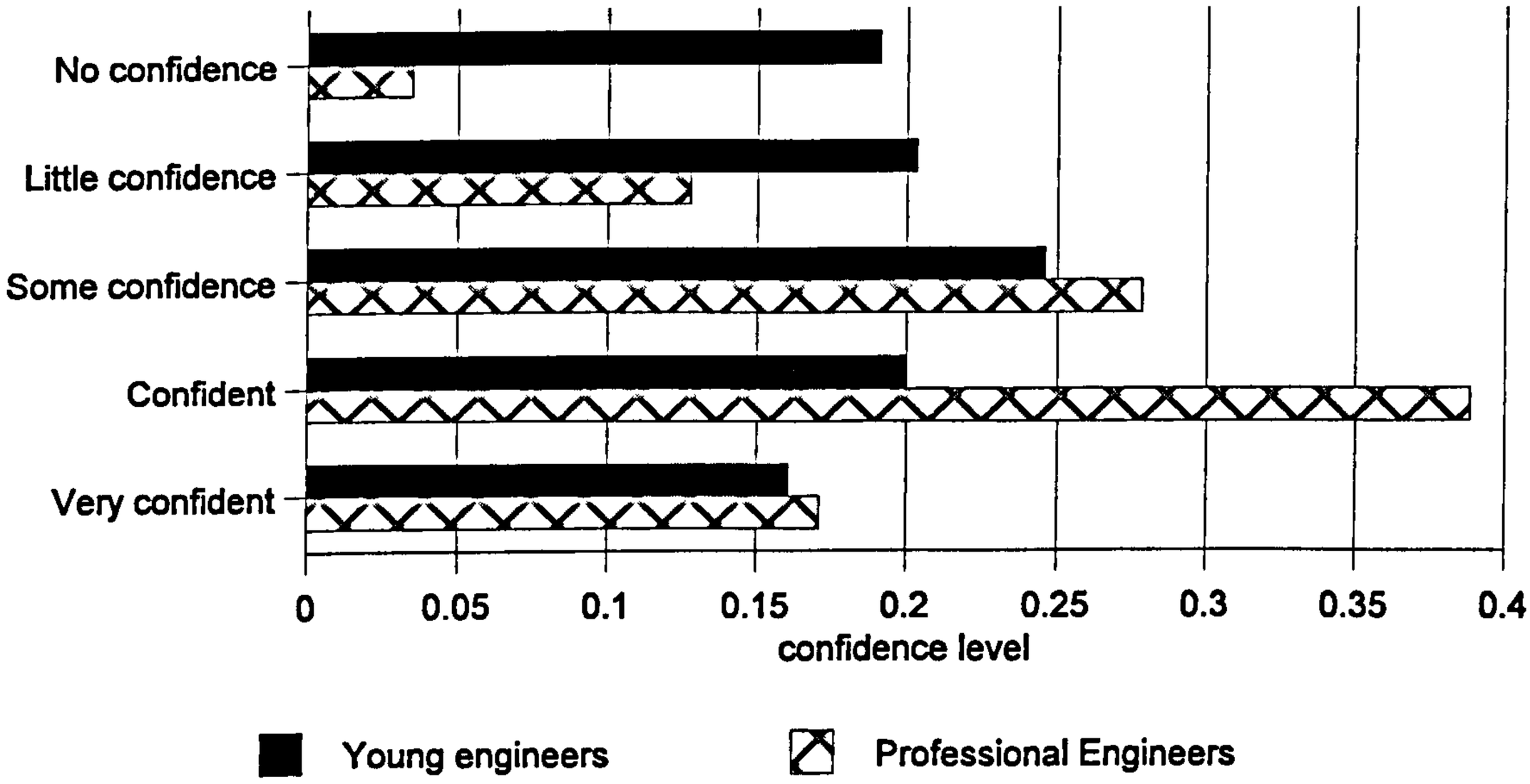


Figure 16.1 Confidence in recognising failure mechanism

As shown in table 16.4 and Figure 16.1, professional engineers are more confident than young engineers in recognising different failure mechanisms. Thus should the expert system be an education tool for young engineers or should the expert system be a reference tool for professional engineers? There could be a process or algorithm that alters the expert system

	Question Related to your needs for a computer system to aid you in undertaking failure analysis as described above	Strongly agree and agree %		Neutral Comment %		Strongly Disagree and disagree %	
		Prof	Young	Prof	Young	Prof	Young
1	I carry out failure analysis often	**61.54%**	22.22%	23.08%	22.22%	15.38%	**55.56%**
14	A definition of a failure relates to a persons perception and experiance	**63.64%**	**50.00%**	18.18%	10.00%	18.18%	40.00%
15	I undertake failure analysis in many fields, e.g. shipping, aerospace, domestic white goods, oil	**53.85%**	20.00%	15.38%	30.00%	30.77%	**50.00%**
16	I undertake failure analysis with many material types, e.g. glass/ceramic, polymer, metals	**41.67%**	10.00%	16.67%	**60.00%**	**41.67%**	30.00%
17	Generally I undertake failure analysis with metals	**92.31%**	**55.56%**	0.00%	11.11%	7.69%	33.33%
2	Engineering failure analysis is easy to do	8.33%	0.00%	25.00%	40.00%	**66.67%**	**60.00%**
3	An expert system for failure analysis is a good idea	**83.33%**	**80.00%**	16.67%	20.00%	0.00%	0.00%
4	To produce an expert system for failure analysis is a difficult undertaking	**83.33%**	**70.00%**	8.33%	30.00%	8.33%	0.00%
5	An expert system for failure analysis would be useful for me in general	**66.67%**	20.00%	25.00%	**50.00%**	8.33%	30.00%
6	An expert system for failure analysis would be useful as an professional tool	**75.00%**	**77.78%**	25.00%	11.11%	0.00%	11.11%
7	An expert system for failure analysis would be useful as an educational tool	**100.00%**	**90.00%**	0.00%	10.00%	0.00%	0.00%
8	An expert system for failure analysis would be useful if all the terms were explained in a fully detailed and unambiguous manner	**83.33%**	**100.00%**	16.67%	0.00%	0.00%	0.00%
9	I require information in an expert system that is at a high professional level (not too simple).	**66.67%**	**36.36%**	25.00%	**36.36%**	8.33%	27.27%
10	I require information in an expert system to have a reference rather than a extensive and detailed description for the failure mode.	**63.64%**	**60.00%**	18.18%	10.00%	18.18%	30.00%
11	I require extensive photographs within an expert system.	**91.67%**	**90.00%**	8.33%	10.00%	0.00%	0.00%
12	A quick and easy to use expert system is very important	**41.67%**	**60.00%**	**41.67%**	30.00%	16.67%	10.00%
13	If the analysis takes longer than 3 mins I would be reluctant to use the expert system.	25.00%	30.00%	16.67%	**40.00%**	**58.33%**	30.00%

Table 16.5

depending on the type of user and their level of understanding in recognising failure

mechanisms. This would affect the questioning and information structure strategy. Table 16.5 details the results from the survey in which the needs for a computer system to aid in understanding failure analysis are asked. The order that the questions were asked was related to their relative importance. The most important was first as it was thought that by this stage in the survey, respondents might lose concentration and not consider the questions fully. However, in the results, the responses to questions were placed relating to the question subject. Thus questions relating to the amount and type of failure analysis (1,14,15,16,17) are discussed first as they are not that important in the survey but important in the discussion.

From table 16.5, questions 1,14,15,16, and 17, detail how often and what types of failure investigations the respondents had undertaken. The responses were typical of the two groups, professional engineers were involved more often than young engineers. This shows that the split between the two groups was correct as this response was required to define the groups. Also these questions showed that the respondents mostly undertook failure analysis in metals. Thus, the choice of initially reducing the scope of the expert system to metals was suitable.

From table 16.5, questions 2 to 4, all the respondents agreed that engineering failure analysis was not easy to do and that an expert system for failure analysis was a good idea although a difficult undertaking.

From table 16.5, question 5, most young engineers were undecided if a failure analysis expert system would be useful. This relates to their indecision about their career in engineering. This is in contrast with professional engineers would were mostly involved in failure analysis and thus saw the possible advantages of an expert system.

From table 16.5, questions 6 and 7, most respondents agreed that the expert system would be useful both as a professional and educational tool. This is a difficult undertaking as each tool requires a different approach both in written style and content. This is illustrated in question 8 where most respondents wanted information in the expert system to be explained in a fully detailed and unambiguous manner, but also required the information in the expert system to be of a high professional level (i.e. not too simple). This means that a considerable amount of information is required in the expert system as extra educational information. By using browsing facilities on cases, questions, and actions in the expert system this is possible although labourious to do. However, although references were wanted, they were not as important as first envisaged when compared with the loss of detailed information (table 16.5, question 10). For other information most respondents required extensive photographs within the expert system.

Although most wished for a quick and easy expert system, (table 16.5, question 12) this did not exclude a more complex system that would take longer in its analysis (table 16.5, question 13).

16.4 Survey discussion

The survey although generally successful, was complex and asked too many questions. Although it was a good idea to collect this detailed data, the numerous questions might have caused people to skip over questions without fully examining the meaning. Thus if a subsequent survey was to be undertaken far fewer questions would be asked. During the research, the survey design evolved through personal feedback and information required by the author to aid the development of the expert system. With the current results a survey with a greater focus on the problems of development could be developed discussed in chapter 19.

Grouping respondents into professional and young engineers proved that the difference between the two groups was not as great as first envisaged. Although professional engineers had more experience and confidence in recognising failure mechanisms, their areas of reduced confidence were similar to those of the young engineer. Thus, the expert system that was based on covering all types of failure mechanisms and providing extensive information through browsing, was correct as it provides an expert system suitable both to professional and young engineers. However, as time and resources are limited, it has been argued that greater emphasis should be given to either common failures for young engineers and less common failure mechanisms for professional engineers. Although such a system might be simpler to construct, it would not reduce the propensity for components to fail. This is illustrated by the high numbers of common failures that occur after being designed by professional engineers as discussed in chapter 15. Thus providing extra information to professional engineers is likely to reduce failure. As this is the aim of this expert system, the ideal system would cover all failure mechanisms with at least some information. This information, as expressed in the survey, would ideally include full descriptions written in a clear and unambiguous manner covering all failure mechanisms with detailed photographs. However, sourcing and structuring this information is extremely difficult and thus central to the knowledge engineering problems encounter in developing this expert system.

Chapter 17 Discussion

17.0 Background

It would be an over simplification to say that only a computer program has been developed for failure analysis, and that the research consisted of simply writing the programming code. First it must be noted that this case based reasoning failure analysis expert system is the only one ever developed, although considerable efforts have gone into developing other types of systems in the past (Chapter 2). Failure analysis can give very detailed information. However, it is extremely complex. This is illustrated by the multiple meanings related to what constitutes failure (section 4.1). Thus a considerable section of this research has been on investigating failure analysis, assessing the feasibility to it being the domain of an expert system, and the engineering of the failure analysis knowledge into a structure suitable for inclusion into an expert system. Any expert or knowledge based system is useless without a clear method by which the information can be represented, so research had to be undertaken to investigate techniques of representation (text, graphics, and the world wide web). The accuracy of any expert system is based on the accuracy of the inputted information, thus evaluation of that information together with methods to validate and increase the accuracy of information were also researched (data mining, and user survey).

Thus there were seven major tasks involved in the research:

1. Examine the problems involved in failure analysis and previous expert and knowledge based systems, with a discussion of the issues involved in failure. (Chapters 1 to 4)

2. Consider the feasibility of designing an expert system for failure analysis. (Chapter 5)

3. Consider the most appropriate software and hardware integration specific to the failure analysis diagnostic expert system. (Chapter 5)

4. Knowledge engineering of failure analysis information for acquisition and development of cases, actions, questions, and rules to answer questions, with an understanding of the semantics (search and ignored words). (Chapters 6 to 11)

5. Knowledge representation through text and graphics within different computer systems. (Chapter 12)

6. An evaluation of the expert systems performance.

7. The development of other techniques to aid diagnosis and reproduction of failure analysis information, including a world wide web based expert system, datamining and a user survey.

The main reason for this research was to reduce the propensity for failures through the development of computerised applications. This very broad aim becomes clear when it is known that many failures occur repeatedly although remedial actions, design and material changes are well understood by expert engineers. However it is likely that all engineers are unaware of all the critical failure routes and this is not helped by the continuous development of new materials, designs and manufacturing processes. Thus many engineers are ill-equipped to examine failure problems and this coupled with the lack of readily available information, means that failures and remedial solutions are inadequately diagnosed, leading to a high propensity for the failure to recur as illustrated in Figure 17.1. This cycle continues until the engineer is fully educated in diagnosing a given failure mechanism. An expert system that could provide assistance to the engineer in collecting relevant information and initiating diagnosis could reduce the frequency of this failure cycle. The ideal scenario would be an expert system that could replace an expert failure analysis consultant. This is unlikely to occur in the near future due to the complexity of failure analysis; computer systems can only yield approximate results, whereas human experts can recognise the limitations of their knowledge and use their creativity, to solve new failure problems. Thus, a suggestive aid to the engineer, providing relevant information and diagnostic tools is more appropriate, and that is where this expert system is aimed.

Although there are many computer systems (Figure 2.1), computer systems to aid failure analysis are very limited, partly due to the complexity involved, but also due to the lack of personnel involved in both failure analysis and computer programming compared with other fields. However, this is rapidly changing with the increased ease of program production (high level visual and object oriented programming languages) and information reproduction, (WWW, multimedia, etc.). Although, artificial intelligence and expert systems have considerable developments these have not been utilised fully, in failure analysis (section 2.1).

Most expert and knowledge based systems have been developed based on similar architectures. New advances have been in the different methods for knowledge acquisition (natural language, object manipulation, etc.) and representation (hyper-text, visual modelling, etc.) (section 2.3) and in the move from purely rule based systems to other reasoning methodologies, such as case based reasoning, fuzzy logic and neural network (section 2.4).

Presently, no computer systems fully encompass a true generic failure analysis expert system, although this expert system attempts to be such a system. To be truly generic entails analysis of all failures related to all materials, products, and manufacturing processes, with consideration of all possible end uses whether designed or not. However, a few systems could aid in certain specific failure investigations and so that this expert system did not recover existing work, analysis of the existing systems was undertaken (Chapter 3).

The expert systems in existence can be categorised as programs based on, standards (PD 6493:1991), domains (bearings, bridges, boiler tubes, etc.), past designs (FMEA), individual failure mechanisms (mainly fatigue and corrosion), and materials selection (Chapter 3). The benefit these systems provide in the development of the expert system was to reveal what made a successful and a not so successful expert system. Successful expert systems result from small-manageable domains, where the choice of problems led to solutions of real economic value. Many expert systems tried to undertake too much, and this was generally because management wanted to get a return on the investment. Thus strong support from management and the use of controlled incremental prototyping, was also seen as important.

A major problem in the development of expert system is the collection of relevant information. It was hoped that some information could be gained from other systems. Much of the data within the systems detailed in Chapter 3 was not directly useful for the development of the expert system as most was embedded within the program and non-transferable. This was especially so with the older systems. The newer systems detailed in Chapter 3, had more relevant data that was easier to transfer, but was protected by international copyright laws and thus was not used.

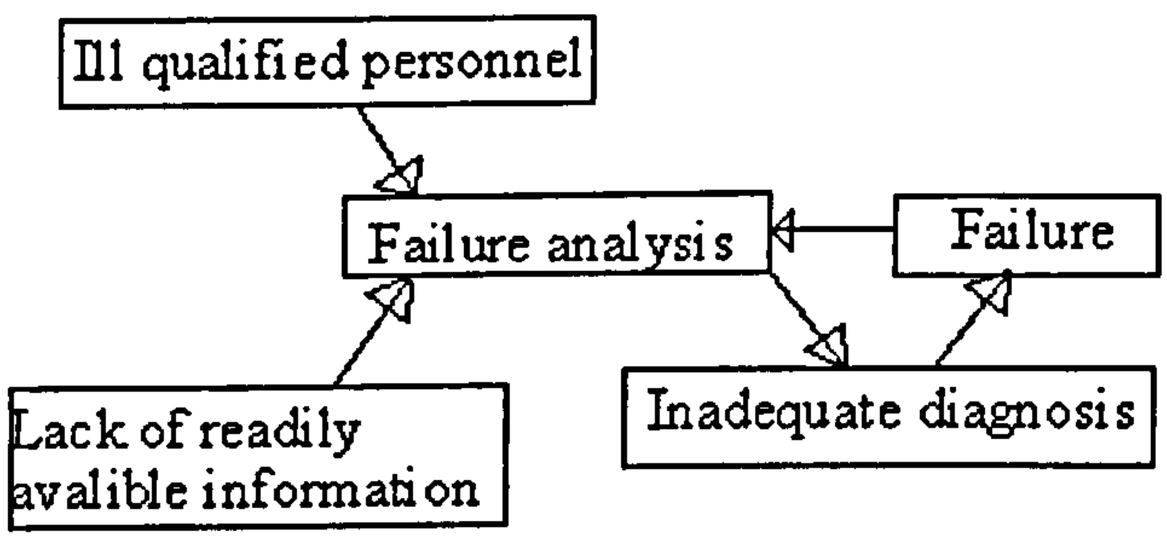


Figure 17.1 The recurring failure cycle.

Of greatest interest to this research were the expert and knowledge based systems developed around different failure mechanisms such as fatigue and corrosion. Although these systems, are generally successful, they tend to be limited to individual failure modes, while failures in general do not have a single failure mechanism. In addition, what one person considers a failure can be completely different compared with that considered by another as their perception of what constitutes a failure is affected by their educational background, the time and location of the failure and the public and media understanding of failure (section

4.7). Thus, the information from any failure analysis expert system may be flawed without either the correct personnel or information which covers all personnel. However, even if an expert system could diagnose that a given failure mode has occurred, that does not necessarily mean that the expert system knows why that particular failure mechanism occurred and not another. For many failure cases, knowing why that particular failure occurred is important to reduce the recurrence of a failure. At this point knowing what the performance aims of the expert system are important and whether these aims are feasible for an expert system.

17.1 Performance aims

There is an important distinction between those systems developed with the aim of performing correctly in all or nearly all cases (i.e. to be experts themselves) and those which are aimed at dealing with the relatively straightforward cases (say all but the most difficult 10%), to free the human expert to concentrate personally on the most difficult ones. Developing a system which preforms well on the relatively straightforward cases is not a problem. This is both seen in the literature and in developing a web based system for failure analysis. However to improve such a system so that it can analyse all cases increases the complexity and involves a considerable increase in effort resulting in a much larger system, with a much more complex representation of knowledge. This is the main problem with the present failure analysis expert system.

Which system is more ideal is a matter for debate. In a practical and commercial sense, a simpler system that deals with straightforward cases would be more successful, because the simpler domain would be easier to program correctly and that straightforward cases means common failure modes, which are more likely to occur and be found by the expert system. It has been noted from the survey undertaken (Chapter 16) that such a system would be used by engineering students and young engineers as an educational tool. However, it would be unsuccessful as a practical tool for an expert in failure analysis as it would lack the less common failure cases. The main performance aim for the failure analysis expert system was for a system which could cope with all failure cases. This was based on a certain naivety in developing such systems, which has later proved near impossible within the field of failure analysis. In some fields developing a high performance system may be essential and from an academic viewpoint may lead to greater insights into the field and the problems of building such an expert system. From the work done in developing the failure analysis expert system, great insight into expert system development and the structuring of failure analysis knowledge has been gained. However the complex nature of this task has lead to performance loss, in that it does not at present correctly identify all the different failure modes. In reflection a lower

performance aim would have been more successful, but to the detriment of the academic insights into expert systems and failure analysis. Thus, considering the main aim of developing an expert system is important for companies. Is it for the expert or is it for educational use? There is an increased risk of failure, but a greater insight into the problem, when developing expert system with high performance aims. There is a greater probability of success in developing a system for education or ones which free up the experts time by correctly handing simple and straightforward cases. It could also be argued that the human expert is more likely to find the latter approach considerably less threatening and thus may be more likely to cooperate in system development. During the survey (Chapter 16) and in general conversations with failure analysis experts and other professionals in the consultancy field, (Chapter 5) this opinion was expressed often. This was partly due to the experts wishing to protect their careers, but also needing the expert system to support their consultancy work, but not to replace their role as a consultant. It is considered by the author that the possibility of their role being replaced by a "super" expert system in very unlikely. It is the author's opinion that the performance aim of the expert system should help facilitate the easing of the consultancy task by providing the consultant with readily available information which would deal with the relative straightforward cases and help the consultant with the more complex cases.

17.2 Failure investigation

If the expert system is going to be used by an expert consultant during a failure investigation, knowing how a consultant undertakes a failure investigation and how to integrate the expert system into this investigation is important. Sources of information describing the different methodologies for failure analysis, are limited (section 4.4) and dependent on the objective of the investigation (i.e. affix blame, fundamental (commercial) and academic investigations) and this relates to the level of controls and detail of analysis. Thus, most organisations undertaking failure analysis have generally failed to put sufficient emphasis on the need to develop and encourage the science of failure investigations and the dissemination of resultant information due to commercial confidence and the lack of accessible and confidential channels. It is here where an expert system can be an advantage. However, two individuals from different backgrounds using different methodologies might arrive at a single correct answer or three different and equally valid answers to the investigation.

A failure investigation can be split into three sections relating to which failure mechanism occurred, why did that failure mechanisms occur and not another, and what remedial actions to undertake. They require an increasing level of information, yet they all follow similar paths of problem definition, background information collection, preliminary investigation, testing,

analysis and conclusions. The complexity increases when more information is required. Thus, is it truly feasible to develop an expert system for failure analysis?

17.3 Feasibility study

An examination into the feasibility of building an expert system for failure analysis was undertaken (Chapter 5). It considered the necessary requirements and justification for the expert system development. It concluded that the task of failure analysis did not fully require common sense and a physical approach, as most initial decisions were cognitive as the failure analysis information could be symbolic and heuristic in structure, i.e. could be analysed from facts. It was also concluded that the appropriate experts and published information was available and the domain, although complex and extensive, was fairly stable being based on real data (case histories with specialised vocabulary). Due to the complexity of failure analysis it was considered unsatisfactory to use a conventional (algorithmic) computer program although some degree of incorrect or non-optimal results can be tolerated. This all led to the conclusion that in theory, the development was possible. However, was this development economically and socially justified? Considering the immense losses, both human and financial, from failure, and the scarcity of failure analysis consultants, and that the expert system could rapidly and consistently provide failure information in many locations and environment simultaneously, the development was considered justified.

17.4 Software selection

Although failure analysis was considered feasible as a knowledge domain, this failure knowledge is complex and unstructured, thus acquisition wholly into rules would be impossible. A combination of cases and rules which suggested several possible solutions would be more appropriate. Finding a development programming application which would complete this task was more complex. First the hardware platform was considered and based on the largest user-base, the IBM compatible computer (386, 486, and Pentium processors) using Microsoft's Windows (3.1, 95, 98, and NT) as an operating system was chosen. The chosen programming environment was the lowest specification and thus the largest user base, which was a 386-processor running Windows 3.1 (section 6.2).

Deciding which of the different software options to use was more difficult compared with deciding which hardware platform to use. However analysis of the requirements (Chapters 1, 4, and 5) and by comparing those against present software methodologies (Chapter 2, 3) selection criteria were developed and ranked by importance. These were inference/reasoning technique, ease of programming, performance, ease of up grading and cost. These are given in order where the inference/reasoning technique was the most important and cost the least

important. It was concluded that case base reasoning was the best inference technique and CBR Express, being the most popular case based reasoning application tool, was chosen with its associated runtime version CasePoint. To aid the representation of failure information, other programs such as ToolBook, Visual Basic, and web pages in HTML, could be linked to CBR Express and CasePoint (section 6.3).

17.5 Cases, questions, rules, and actions

The choice of programming tools and expert system shell affected the approach in using and programming the expert system. Being a case based reasoning expert system, the approach was the matching of a failure situation against a collection of stored failure case histories. In this respect, the case based expert system is only as good as the number of cases stored, with which comparison are made. Thus, given any failure situation, if only one case is stored in the case base then the only answer the expert system produces is that single case. Therefore the more cases the better. However without the correct reasoning (questions, and information structure) strategy, matching would be inaccurate. But what constitutes a truly functional set of cases, questions, rules, and actions? It was found that to include all materials other than common industrial alloys would be problematic, due to the vast amount of information required. Although this could be expanded in future versions, it was felt that the field of common industrial alloys was large enough to analyse the complexity of the problem yet small enough to be manageable. Even with this limited number of materials there are a considerable number of failure modes and considering the expert system is built on actual failure cases histories, the numbers of actual cases which could be added to the expert system is only limited by the human typist and the possibility of repetition. However, each failure can be very different from the next thus the chance of repetition is limited until considerable numbers of cases have been entered into the expert system. This highlights a problem in development in which the developer could have spent the whole research time adding interesting and valid cases to the expert system. Although considerable time was spent in adding cases, this did not necessarily lead to either an all round effective expert system or contribute significantly to the field of research without involving other areas (WWW, multimedia, datamining, question and rule strategy, and semantics) of research. Thus cases were developed from a list of common failure modes based on what initiated the failure and not the outcome. However, there were some failure modes which had more than one case, but this was controlled because no bias from either the developer's educational background or from the failure case history source was wanted as it was intended that the expert system was for generic failure analysis.

As the most clear-cut characteristic of a failure mechanisms is its remedial action, therefore the cases and associated questions were written first, then the actions were considered. It was found important to have the same type of questions within a case subgroup, e.g. fatigue, so that all the cases within a subgroup are affected by a question.

17.5.1 Cases

The case title and description form the basis for the first search from the natural language input. Describing this uniquely to identify the failure mode was complex as many cases could be similar. For example, stress corrosion cracking in aluminium could have a similar description to stress corrosion cracking in stainless steel. It was found extremely important to emphasize the unique features that make the failure mechanisms different, without loading it with obscure terms that the user does not know which may be absent from the natural language searching. However, three or four different alternative terms can be used to describe the same thing. Therefore, a thesaurus of standard failure analysis terms was developed to guide users into the correct terminology (See section 8.2). Case descriptions were kept to the same length (four lines of text) to help the expert system perform a more accurate initial search. This does restrict the possibilities for including alternative terms, as extensive alternative terms mean either a long description and a slow performance; or the description being a series of alternative terms which will not differentiate the different cases adequately. Another difficulty with length, was making the descriptions grammatically correct, as there is the possibility of using a series of related terms. However, a balance has to be drawn between being written well and having enough related terms to differentiate the different stored failure cases. With the increases in computing power, performance issues associated with long descriptions is not a real problem. However, selecting enough relevant and defining terms is more complex as extensive terms would not differentiate cases as each case would have similar terms, so a critical balance has to be made. Further work investigating this issues and with the possibility of increasing the number of lines should be undertaken.

17.5.2 Question strategy

An effective questioning strategy involves: selecting the description, selecting the question order, assessing question weighting, assessing which question types (yes/no, list) to use and selecting the number of questions by which to detect the most important facts (Chapter 9). Some information is well known and generally requires little analysis. Such questions are easy to answer and therefore should be the first to be answered, e.g. What process /component /material?; What temperature? Room, Elevated, High; What time to failure? Very short, Short, Long.

Most information in failure analysis is very difficult to quantify. Typical examples are stress levels at stress raisers, or pH levels for local concentrations of solution. These can be measured in a static state, but as most systems undergo dynamic interactions with their environments, these factors are difficult to measure. (See Table 9.1). Thus questions related to information that is readily available, for example static stress states, general environmental conditions overall material compositions, and main manufacturing methods as other information was likely to have considerable errors especially if the values or processes are guessed. Although the answers to, for example, "What force? Steady or Cyclic." or "what primary manufacturing method" seem vague, inferences were made to different failure mechanisms. Information that is readily available is generally found by looking at an easily observed situation. Also by designing questions to ask for easily observed situations meant that all possible users could answer questions.

With the complexity of failure analysis and the many easily observed situations, many questions could have been developed. However excessive questions (more than 50) are not ideal because answering becomes labourious. Also, excessive questions means question design and maintenance becomes too complex and thus unreliable in its logic. The only way found to keep the number of questions low was to combine similar questions. These included questions on materials, manufacturing processes, environmental conditions, and stress levels. Extra information relating to questions was found useful by all evaluators, as it explained the reasons and meaning for the questions. This was especially so with non-experts and young engineers where, without this extra information, many more much simpler questions would be required, which as detailed above, is not ideal.

Initially, many questions were specific to a single failure case. This was not ideal as it could have lead to one question to each failure case and thus an excessive number of questions. Therefore through evaluation many case specific questions were combined to produce generic "Yes/No" and "List" Type questions. However, the process of developing case specific questions was needed so that incorrect preconceived questions were not developed.

17.5.3 Rules

Developing an effective failure analysis expert systems solely on past failure case histories, entailed many cases which complicated the similarity matching of different cases, especially as there was ambiguity in the questions and answers. This lead to the similarity matching of too many unrelated cases as answers. Although many expert systems could be based solely on past case histories, in failure analysis it is best to develop deductive *(whenever-then)* rules. The rules answered questions from keywords found in the initial search description. Most questions could be answered by one keyword. This was found very successful in improving the accuracy of analysis. Rules were associated with questions either because the keyword directly related to the question (brass in the description would answer the materials question) or an engineering failure relationship was self evident (cyclic or fluctuating stress suggests fatigue). Some trends were sometimes not so self evident and it could be argued whether or not they are an accurate representation of a relationship especially as the number of cases increases in the expert system, i.e. wrong associations being made. An example is as follows: WHENEVER "H_2" or "hydro" or "water" THEN answer question 9 " Is there a source of Hydrogen within the environment" YES. This is associated with Hydrogen. This may be so in a number of failure cases, but not necessarily in for example a civil engineering failure of a dam.. Although there are many terms which could be developed into rules, covering every term would produce an inflexible (rule based) expert system without the benefits of case based reasoning.

17.5.4 Actions

Actions are extra sections of information that explain solutions to failure problems defined in cases. Initially one action, one case was envisaged, but further evaluation detailed some failure mechanism with many possible solutions, thus generic actions were designed to be shared by cases. This quickens development and un-clutters the system (section 10.0, 10.1).

The information within actions is a balance between just enough for a non-expert and not too much information for an expert. Although, in theory there is no limit to the amount of information possible, without the correct and directly relevant information, the action becomes ineffective because finding the remedial solutions and preventive measures could become difficult. Thus, actions were specific to an area with the minium textual information possible. However some actions covering more basic failure mechanisms, e.g. corrosion, had extra information for the education of young engineers, who would more likely examine extra information in more common failure mechanisms compared with professional engineers (chapter 16). The most suitable actions were those developed into multimedia applications

using hypertext links and photographs (chapter 12). This allowed users to browse information at their own pace and requirements.

17.6 Semantics

As the expert system uses a natural language interface to collect and process the initial search description, an examination of the possible words used proved useful. English, like any other language which could have been used, has an extensive vocabulary, some of which expresses the same concept and some expresses grammatical structure. The words entered at the natural language interface are sorted and compared against the stored case description for a similarity match. The sorting involves excluding specific words to leave keywords which either fire rules to answer questions or are matched against cases directly. Problems occur when entered and stored words have the same meaning yet different letters, or are used incorrectly to describe a term or situation. To reduce this problem, different words with the same meanings were included in case descriptions and an extensive list of excluded words was developed. Excluded words included, common words, commonly confused abused and mistyped words, similar words, homonym, and other filler words such as articles, pronouns, conjunctions, prepositions, and interjections. Common words were developed from a word usage assessment done on the expert system. Excluding these words even if they are keywords would aid diagnosis, because the common nature of that word would not differentiate different cases. The other excluded words could be seen as words which describe objects, i.e. nouns. Full advantage has not presently been gained from excluding words as programming difficulties have excluded their inclusion, and thus further work is required in this area.

17.7 Knowledge representation

Any knowledge detailed by the expert system has to be presented to the user in a detailed and unambiguous manner. Methodologies for this knowledge representation have been discussed, they include multimedia and world wide web (WWW) applications. Within this work ToolBook (chapter 12) and Hyper Text Markup Language (HTML) (chapter 14) was used to demonstrate these methods and their advantages and disadvantages over conventional representation systems (i.e. plain text, and printed information). Emphasis must be placed on demonstrating these methods as for both methods there was a lack of readily available, copyright free, information, and the production of new information free of copyright restriction is time consuming because for every copied diagram, photograph or sentence, copyright clearance must be sort from the originator or author of the information resource. Addressing this problem is fundamental to a successful multimedia or WWW development. With the association of this work to the Engineering Materials Consultancy Service, at Southampton University, many photographs were available copyright free to this project.

Although both multimedia and WWW applications are a collection of photographs and text, the difference between these applications and other conventional representation systems is the hypertext and hyper media links between the resources. These links allow users to browse information at their own pace and information requirements. However, issues such as human to computer interactions, software psychology and ergonomical/cognitive ergonomical considerations mean that a structured approach to design is required (section 12.1). This meant the design, placement, size, and colour of backgrounds, buttons, photographs, printed images, etc. was directly assessed as to its impact on the user (section 12.2). There are many possible design configurations possible, yet the purpose of these applications is to transfer information efficiently. Thus a cluttered, application which uses the development tool to its full extent, might only convey the ability of the programmer rather than the information. Thus the underlying design principle within these applications was to have the minimum requirement for the required information delivery, which lead to the development of a common layout (section 12.6).

17.7.1 The Internet

The Internet is seen as the next step for the presentation of information after multimedia. Its growth is undeniably obvious and rapid. Its advantages are in the transmission of information to any location in the world, where this information could be video, audio, photographs, and text. However this is not as perfect as it sounds because there are bandwidth transmission bottle necks which slow down the transmission of information and economic and social problems as to who pays and who controls the information. Until these two major problem areas are resolved, future developments are limited to either the advertisement or goodwill of an organisation. Another problem with the Internet is achieving revenue from online information. Although attempts by different organisations by emailing credit card details are possible, fraud through the theft and inappropriate use of credit card details is common (the author has first hand experience of this theft). Thus until a secure payment method is devised and bandwidth problems are addressed the WWW will not develop to replace other electronic, digital, or magnetic recording techniques that might hold a multimedia application. Yet these problems will be solved and thus analysis of WWW methods to aid failure analysis were investigated (section 14.4).

On-line search facilities are the most useful application within the Internet for information on failure analysis (section 14.1.3). However, the information found is either text, or graphics, and does not analyses failure problems and suggest areas for further investigation as an expert system would. The information can be extremely useful if relevant, but there are considerable amounts of irrelevant information produced by on-line searches. Methods to integrate this

expert system's knowledge on to the Internet have been investigated. However with any WWW development, it is a matter of intelligent design rather than elaborate graphics produced by clever programming tools. Being such a visual media, the presentation design is important to convey the information. Thus considerable effort has been investigated into suggesting good web site design practice relevant to failure analysis (section 14.5).

17.8 Improving the performance

With the building of the expert system, many assumptions were made about the knowledge. These included the relative occurrence of different failure mechanisms, the computing ability and needs of possible users and their level of understanding of failure analysis. These initial assumptions, were based on commonly held beliefs, such as fatigue occurs more than creep, possible users are computer literate and require detailed relevant information, although their understanding of failure analysis is limited. These assumptions are correct, and help the expert system author improve the reliability and accuracy of information given to the user. However, these assumptions had to be assessed before their use in the expert system could be validated.

If the relative occurrence of a failure mechanisms compared with others can be proved with some degree of accuracy, then this values can be programmed into the expert system, so that before any information was entered into the expert system a general level of confidence can be associated with different failure mechanisms (chapter 15). This analysis was undertaken by examining the number of documents with keywords associated with different failure mechanisms, the documents being held as references in on-line data bases. Although there are many problems with this technique (section 15.4), the data is significant enough to suggest the relative occurrence of different failure modes. The relationships observed relate to time, on-line location, and keyword used. It was observed that a cyclic change in hits occurred, but with an overall increase in hits with time (section 15.2.1). Without further investigations, precise reasons for the cyclic and increasing number of hits can only be suggested for further investigation, but the economic climate and the increasing opportunities or stimulus to publish papers must affect the number of hits. This is further illustrated if the investigation is carried out on several on-line data bases, as the trends are similar in relative magnitude although different in actual number of hits. By examining these figures over 18 years, a normalized average can be found, which can be used to develop an occurrence ranking for different failure mechanisms (section 15.3). Although not presently used, it has proved itself for further investigation and inclusion in to the expert system.

The initial design assumption that possible users are computer literate, and require detailed relevant information, although their understanding of failure analysis is limited, was based on

the belief that the users are likely to be engineers from different educational and professional background. However, this assumption had to be assessed as it related to the level, quantity, and type of information held in the expert system. Thus a survey was undertaken to assess the possible users and their computing ability, to assess their understanding of failure analysis and different failure mechanisms, and what was their information needs within the expert system.

The level, quantity and type of information possible users actually require is often different from what they want, i.e. they may want elaborate graphics, animation and sound whilst what they really require might be a database. This influences the choice of expert system technique. A user might want loads of information but this can be impracticable and a development problems. However, some users want very focussed information given on their particular area of interest. This can be easier if the domain is very small, but with a generic system this is also a problem, in that both systems require vast amounts of information, although the former would work with a less intelligent system. It is thus seen that the latter would be more complex to produce in a generic system. From the survey, people are very much split about what information they require, as they wanted all terms fully explained in an unambiguous manner, but also at a high professional level that was not too simple, and where there are references rather than an extensive and detailed description (section 16.4, table 16.5). This does not make sense, because there is a split to either having lots of information on all areas for education and to initiate the thought process or to have focussed information purely to solve a given problem. However, what is actually required to both educate the user and aid in failure analysis problems? In an ideal situation both types of information would be available, probably through an extensive database of information on which to draw. This is a very difficult and time consuming to develop personally, with many associated problems, such as copyright issues and the supply of relevant information. Writing a large database would be similar to writing a large book on failure analysis. Thus methodologies that showed a problem area and supplies just enough information to suggest where more information can be found or what to do next is all that the users really required. If more information is required then this is more in line with a multimedia package or an extensive web based application to which the expert system could be linked.

With the survey considering the needs of the users, the evaluation study examined the resultant expert system's performance.

Evaluation was carried out by the author throughout the development of the expert system. However, it was highly likely that this was biassed as the author knows how the system works and what abilities it has. Thus, a fairer evaluation was undertaken by others associated with

the development of engineering software. Overall they appreciated that the expert system was still in development but the overall structure of case based reasoning was well suited to failure analysis. Many had to be educated on the benefits of case based reasoning compared with other reasoning tools and programming languages which were more related to their fields of work. All respondents said that it was a difficult domain in which to develop an expert system and this was confirmed by the survey results. Most comments on the performance of the expert system were positive. However, although positive responses are a confirmation that the correct approach in development is being used, they offer little in real feedback. The very few negative results received offered more detail to aid development. These included the need for more cases which are less specific, and for the supply of more information. More cases would increase the accuracy of diagnosis and more information would aid finding a suitable remedial solution to the problem, and this is covered in the further work section (Chapter 19).

Chapter 18 Conclusion

1. Most failures occur in metallic structures, where deformation, fatigue, fracture and corrosion are the most common failure modes. Premature failures are a daily occurrence partly due to the lack of readily available information, poor education and the complexity and inaccuracy in correctly diagnosing and recording past failures.

2. Although there are many different computer programming techniques, an expert system was seen as a good way to make failure analysis case histories more widely available to aid investigation and reduce the propensity for recurring failures. Investigations found that most expert systems were based on rule-base reasoning and were successful expert systems if the domain was small and manageable. However generic failure analysis is not a small domain and the information is normally presented as cases rather than rules. Recently case based reasoning expert system shells have become available. Hence the development of an expert system for failure analysis based on case based reasoning was considered more appropriate and was undertaken.

3. An effective failure analysis expert systems, based solely on rules or past case histories, entails either a complex set of rules or many different cases histories. The best methodology is a hybrid approach, which uses both rules and case histories as this mimics the approach used by failure analysis consultants. Thus, a prototype hybrid case and rule based reasoning failure analysis expert system based on generic metallic failure case histories was developed to aid failure investigations both as a professional and educational tool.

4. Capturing failure analysis knowledge into an expert system is extremely complex. However it has proved feasible if the appropriate personnel, information and software tools are readily available. Software selection is fundamental to a working expert system, especially as it affects the collecting and structuring of knowledge which in this research was to knowledge engineer, cases, questions, rules, and remedial actions for a case based reasoning expert system shell. The information was collected from past failure cases and generic design failure situations to give a broad selection of the different possible metallic failure mechanisms. Several important issues arose, such as which failure mechanisms should be covered, what questions will be most effective, which keywords fire rules, what level and type of information is required.

5. To aid the representation of information, multimedia and world wide web HTML applications were important especially with the hyper-link browsing ability associated with

these applications. Engineers are able to examine information at their own pace and selection. The main problems involved the collection of copyright free text and graphical media.

6. With the large amount of information in the expert system and the natural language matching algorithm, semantics became an important issue. This lead to proposing a standardised vocabulary and excluding words from the natural language search. The excluded words should include terms which were either commonly confused and abused, similar words, homonyms, or filler words and nouns that did not, in any way, relate to failure analysis.

7. Future methods to improve the accuracy of the expert system include excluding extra words from the natural language search and the datamining of different databases to assess the probability of a given failure mechanism occurring.

8. Through evaluation and a survey, it was concluded that failure analysis was considered a complex task where an expert system would be an ideal tool. The expert system has been designed so the possible users could be both professional and young engineers, receiving detailed and general information through browse facilities in the expert system. A favourable response to the expert system was received although more work is required to develop it into a commercial package.

Chapter 19 Further work

Although the expert system is able to diagnose failures, it must be time considered whether the expert system shell is to be changed to another version or system. At present the runtime application is CasePoint by Inference corporation, which although extremely suitable for this task, is expensive to buy and licence to other users. Thus, further work would have to investigate either a reduced licence fee or another programming application. Acquiring another programming application, will involve transferring the knowledge across. However, the majority of the work needed for a case based expert system has already been done, because the failure analysis knowledge has already been structured into cases, questions, actions, and rules.

If the present expert system shell is used or any other similar expert system shell, then the following suggestions to improve this expert system should be considered.

1. Use past failure case histories to evaluate the expert system the idea being to identify areas of recurring failure mechanisms where additional cases may be required. Additionally the broadest selection of failure case histories should be included to improve failure diagnosis. These extra cases could be either generic or real cases.

2. Interaction with failure analysis consultancies such as The Engineering Materials Consultancy Service (EMCS), Metaltech, and others to access their failure case histories so that reports may be included in the expert system as further cases. Additionally these reports could be scanned to encapsulate reports and photographs to develop more multimedia applications and on-line documents. This would also save experience that otherwise would be lost and make these files more readily available to the different organisations.

3. Identify what additional information and features could aid the communication of failure analysis knowledge, i.e. graphics, photographs, drawings, text, etc. For example:- the question "Is the fracture surface either brittle or ductile" would mean showing images of ductile and brittle fractures. This could be either through a multimedia application, hypertext browse facilities in questions and remedial actions, or via an on-line document. Although the multimedia applications and browse facilities are based with the expert system, great advantages can be envisaged with linking to on-line documentation that could be located anyway in the world. For example, if a user found that the main cause of failure was an uncommonly occurring failure mode such as brinnelling, an embedded link to an on-line database or web page could be included. The main advantage would be that the link to the

external computer would hold regular updates of research findings, past failure cases and remedial actions. However to make this work successfully, control over the content of these sites would be required. Decisions on what type and level of information required, also need to be considered. However, it could be assumed that all users have limited understanding of failure analysis and failure mechanisms and so an educational approach to all documentation, with on-line browse facilities could be considered more appropriate.

4. Identify what additional information or possibilities could be gleamed through datamining and whether this methodology can be used to influence the matching scores between cases. Ideally many more databases would be searched and many more related terms (i.e. metal fatigue) and non-related terms (i.e. human fatigue) should be considered. This analysis could then be used to affect both questions and their weightings, so that a commonly occurring failure mechanisms would be given extra bias in the expert system.

5. Examine computerised dictionaries, data bases, and on-line sources to discover more words which could be excluded from the search algorithm. Examples of this could include other failure analysis reports and on-line databases such as Compendex, Metaldex and First Search, etc.

There have been considerable programming problems in introducing the list of excluded words into the expert systems search routines. This has been due to compiling problems with Microsoft Visual C++ version 1.53. The list is taken as a *.sym file and converted into a *.rc file. Methods to simplify this operation need to be undertaken for a faster operation of the expert system

6. The development of further rules is in two areas. The first one is to expand the rules fired by the initial description to include other words that are not related to failure analysis or words which confuse either the expert system or the user. Secondly, to integrate rules fired from the answering of one question in order to answer several other related questions. With rules like this, more questions could be included without putting extra strain on the users. Additional rules either through the initial description or via other questions will improve diagnosis. However, there is a limit to the number of rules before the expert system becomes inflexible and thus loses the advantages of being a case based reasoning expert system. When comparing the two methods, it is the linking of questions to questions by rules that will give the greatest future benefit because the present set of rules have covered most areas that can be answered by the initial description.

7. Sometimes cases and questions will be seen in the lists that do not seem pertinent to the current failure case under investigation. Although these cases can be ignored and other questions can be answered, the generation of cases and questions not pertinent to the current investigation case reduces users' confidence in the expert system. The reason for these questions is that the matching algorithm can produce false hits against certain cases, particularly if the search description was vague or very short, or if the case based system happens to be very small. Methods to rectifying this lack of confidence need to be investigated.

One possible solution would require changing the questions associated with different cases and to tune the weighting scores a question gives to certain cases. This is complex and subjective, but ideally a note would be taken of a question and the five highest scoring cases which it affects. From here a knowledge engineer, could fine tune the questioning scores to associate the right case to the question. This initially sounds simple, but when combinations of questions are involved, this form of maintenance and development becomes complex. This might be considered as something that must be done during the development and evaluation stage of producing an expert system. However, due to the complexity of failure analysis information this is nearly impossible to complete due to the many different combinations between cases, actions, rules, questions, and ignored words. This evaluation, maintenance and development will be needed each time a rule, case or question is added to the expert system. Although this extra work may sound difficult and time consuming, it is the flexibility of case based reasoning that allows these changes to improve diagnostic accuracy.

8. The survey although generally successful, was complex and asked too many questions. The numerous questions might have caused people to skip over questions without fully examining the meaning. Thus if a subsequent survey were to be undertaken far fewer questions would be asked but with a greater focus on the problems of development to discover the type of information required by the users and what failure mechanisms should be covered by the expert system. Although it is the aim of this expert system to cover every possible use and have information on every aspect of failure analysis and failure mechanisms, including everything in an unstructured manner is impracticable at present, because the relevant information to reduce failures would become less available and accessible. Hence the purpose of the survey (chapter 16) was to find what information is important. It was clear from the survey that there were common areas between professional experienced engineers and young engineers in their requirements. This should be extended to investigate where differences occur, so the expert system can be adjusted to accommodate both groups.

Targeting the survey at professional and young engineers connected academically or practically to failure analysis meant that there were fewer respondents (24). By visiting other establishments, both educational and industrial, more respondents might be found. If the survey included other engineers not related to failure analysis more respondents would be found, however, these respondents would have to be differentiated from those involved in failure analysis. As many engineering failures have either been designed, procured, or manufactured by engineers not directly involved in failure analysis, their understanding of failure mechanisms and failure analysis could make the expert system more available to the requirements of this group, i.e. from failure analysis tool to design tool.

9. Methods to integrate this expert system's knowledge on to the Internet have been investigated. This was found possible with the new programming tools now becoming available in either a full expert system version or a reduced version which addresses the problems of transmission bandwidth bottle necks. Such a reduced expert system would rely on the knowledge developed in the expert system (section 14.2). However, its programming architecture would be similar to a rule based system with all the disadvantages as detailed in chapter 2. New on-line data base programming tools are in development and these should be available to make a case based reasoning on-line expert system soon, an example of which has been developed by the Inference corporation
(http://www.inference.com/products/searching.pdf) With the advantages that the Internet and the world wide web provides it seems likely that this will be the thrust of future expert and knowledge based systems.

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Appendix 1 Edited programming listing of the cases

Appendix 1 details the cases in the expert system and the answers to questions for a failure case to be diagnosed and thus remedial actions proposed. The details below have be edited from the exported cased based reasoning expert system files, so that the detail remains and the extra programming characters are removed to save space. If a full program listing is required this may be found either on an attached file (jasp9.rpt) or directly from the author.

BEGIN CASE CASE1
TITLE
Incorrect grinding, presence of hydrogen, & fatigue in Ni, Cr, Mo steel
DESCRIPTION : cracking in
Nickel-chromium-molybdenum Steel, (35NCD16), is intergranular and consistent with the existence of high tensile surface stresses.
Stresses result of damage produced during grinding of the surface prior to Hard chromium plating (plated).
Cracking produced by the absorption of hydrogen during electroplating. Cracks led to growth of fatigue cracks Fatigue failure, Hydrogen embrittlement, Crack propagation, Struts, , peening, Incorrect grinding.
ASM Vol.2 History of F.A. pg7.
QUESTIONS
What is your primary material
ANSWER : Ni-Cr-Mo Steel
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the primary process used in manufacture
ANSWER : Grinding
What level is the stress, (High, Low, or No load)
ANSWER : High
Has the component been electroplated,
ANSWER : Hard chromium plating
Does the surface look like a fatigue failure
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
ACTIONS
Use a proper grinding procedure and post grinding inspection

BEGIN CASE CASE2
TITLE
Initial defect led to initiation of fatigue crack
DESCRIPTION : The initial defect was caused during manufacture . This can be seen by a large initial defect
QUESTIONS
Is there any damage near to the possible fracture sites
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High

ACTIONS
Improve the manufacturing process and non-destructive testing

BEGIN CASE CASE3
TITLE
Stress corrosion cracking in 70% Cu, 30%
DESCRIPTION : Failure by cracking under combined action of
corrosion and tensile stress, either external stress or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium
QUESTIONS
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What is your primary material
ANSWER : 70% Copper , 30% Zinc (Cartridge Brass)
Would you consider the environment was corrosive in any way
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
What are the primary environmental conditions
ANSWER : Moist
ammonia, mercurous nitrate (see ASTM B-154), and amines
Are there any other possible secondary solutions in the environment
ANSWER : Rural
and coastal atmospheres
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Is there a source of hydrogen in the component environment
ANSWER : No
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails, threads
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
ACTIONS
To stop stress corrosion cracking

BEGIN CASE CASE4
TITLE
Stress corrosion cracking in aluminum alloys
DESCRIPTION : Failure by cracking under combined action of
corrosion and tensile stress, either external stress or internal stress or assembly stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. In an Aluminum alloy S.C.C can occur in NaCl solutions, Seawater, Water vapour, especially High strength Aluminum-zinc-magnesium type 7000 series.
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
What is your primary material
ANSWER : Aluminum alloy
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Are there any other possible secondary solutions in the environment
ANSWER : Rural
and coastal atmospheres
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Aluminium Alloys
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle

Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : Yes
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What component group is NOT linked or like your component at all
ANSWER : Lifting equipment (Wire, Chain, cable or hooks)
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
To stop stress corrosion cracking

BEGIN CASE CASE5
TITLE
Stress corrosion cracking in gold alloys by FeCl3, Acetic acid-Salt Solutions
DESCRIPTION : Failure of a Gold alloy by cracking under combined action of corrosion and tensile stress, either external stress or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. Gold Alloy effected by FeCl3, Acetic acid-Salt Solutions. This rare failure mode is seen in the microelectronics and jewellery trade.
QUESTIONS
What is your primary material
ANSWER : Gold alloy
What are the primary environmental conditions
ANSWER : FeCl3 Solutions,
Acetic acid-salt solutions
What is your secondary material
ANSWER : Gold alloy
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the component had a surface hardening treatment
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : Lifting equipment (Wire, Chain, cable or hooks)
What primary component group is your component
ANSWER : other
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does your component, have oil holes, grease nipples, etc
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : No
Are there any other possible secondary solutions in the environment
ANSWER : FeCl3 Solutions, Acetic acid-salt solutions
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
ACTIONS

To stop stress corrosion cracking

BEGIN CASE CASE6
TITLE
Crevice corrosion
DESCRIPTION : Crevice Corrosion due to differential oxygen concentration cell corrosion, also called Poultice Corrosion referring to accumulation of moist or wet particles, Dust, Sand, at joint, crevice, interface, between two surfaces, under debris, under fasteners, Nuts & Bolts, rivets. Can occur with similar metals but more corrosive with dis- similar metals.
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Are there any other possible secondary solutions in the environment
ANSWER : Rural and coastal atmospheres
Did the failure occur at room or a higher temperature
ANSWER : Room
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : Yes
ACTIONS
Avoid bolted or rivetted joints unless the metals are coated
Close or seal existing crevices
Inspect and remove deposits frequently
Use solid nonabsorbent gaskets or seals

BEGIN CASE CASE7
TITLE
Possible fatigue failure problem
DESCRIPTION : Fatigue fracture-failure under repeated or
fluctuating stresses having a maximum value less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of the
fluctuating stresses.
QUESTIONS
Does the surface look like a fatigue failure
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Does your component have a keyway
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
Corrosion Fatigue of overlay welded shaft on a ferry stabiliser fin
Fatigue fracture due to abrupt thread run-out
Thermal fatigue in gears
Fatigue calculations
Corrosion fatigue
General overload failure prevention (& fatigue failure prevention)
Processing-induced fatigue fracture in aluminum alloy component.
Remove surface and sub-surface defects to improve fatigue strength
Increase the fatigue strength by surface treatment

BEGIN CASE CASE8
TITLE
Weld initiated fatigue fractures
DESCRIPTION : Weld initiated Fatigue fractures.
Thermal

transformation and cyclic operational stresses initiate cracks in weld material or base material especially if material is hardenable due to fast cooling to Martensite. Problem increased by welding heat being removed too quickly in large and cold materials, poor construction, poor design, welding patches/patch, and other weld deposits
QUESTIONS
What primary component group is your component
ANSWER : welded components
What is the primary process used in manufacture
ANSWER : Welding
Did the failure occur at room or a higher temperature
ANSWER : Room
What level is the stress, (High, Low, or No load)
ANSWER : High
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Is there a source of hydrogen in the component environment
ANSWER : Yes
What is the secondary process used in manufacture
ANSWER : Welding
Is there any damage near to the possible fracture sites
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
If welding electrodes are used, have they been damaged
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Has the failure initiated within a thread run
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What component group is NOT linked or like your component at all
ANSWER : Bearings
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
ACTIONS
Improve your welding procedure
Improve the manufacturing process and non-destructive testing

BEGIN CASE CASE9
TITLE
Fatigue failure of springs
DESCRIPTION : Fatigue failure of springs, spring under compression, stretching, reverse bending or torsional stress \stresses. Typical components to fail include, car suspension, clockwork drives, valve spring.
QUESTIONS
What primary component group is your component
ANSWER : spring
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the surface look like a fatigue failure
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there extensive plastic deformation around the fracture site
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
ACTIONS
Increase the fatigue strength by surface treatment
Improve the manufacturing process and non-destructive testing
Inspect and remove deposits frequently

BEGIN CASE CASE10
TITLE
Contact corrosion, welding with more or less noble electrode

DESCRIPTION : Contact Corrosion, Welding with more or less noble electrode than the bulk material. Welds of this type corrode at either the bulk material or the weld material, due to the electro-potential difference between two different materials
QUESTIONS
What is the primary process used in manufacture
ANSWER : Welding
What is the secondary process used in manufacture
ANSWER : Welding
If welding electrodes are used, have they been damaged
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
ACTIONS
Change the welding consumable to stop corrosion problem
Improve your welding procedure
Impeller failure due to a repair or built up weld with pores
Corrosion Fatigue of overlay welded shaft on a ferry stabiliser fin

BEGIN CASE CASE11
TITLE
Prematurely broken spring due to defects causing fatigue failure
DESCRIPTION : Prematurely Broken Spring due to defects causing Fatigue failure of springs, spring under compression, stretching, reverse bending or torsional stress \ stresses. Typical components to fail include, car suspension, clockwork drives, valve spring.
QUESTIONS
What primary component group is your component
ANSWER : spring
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
What secondary component group is your component linked to
ANSWER : spring
Does the surface look like a fatigue failure
ANSWER : Yes
What component group is NOT linked or like your component at all
ANSWER : Mechanical Fastenings (Rivets, Nuts & Bolts)
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : High
Are there any sharp corners or sharp radii
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does your component have a keyway
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Has the failure initiated within a thread run
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
Did the failure occur at room or a higher temperature
ANSWER : Room
ACTIONS
Replace spring with a higher quality spring
Increase the fatigue strength by surface treatment
Improve the manufacturing process and non-destructive testing
Inspect and remove deposits frequently

BEGIN CASE CASE12

TITLE
Keyway failure due to high hardness of surface and high stress cycles
DESCRIPTION : Keyway failure due to high hardness of surface and high stress cycles, Keyways have small radii. This can lead to stress concentrations and high Kt , Kf values. Also surface defects in that area can also lead to fatigue failure
QUESTIONS
Does your component have a keyway
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Has the failure occurred before the part went into service
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
ACTIONS
Stress concentration factors and how to reduce them

BEGIN CASE CASE13
TITLE
Fatigue failure due to sharply edged formation
DESCRIPTION : Fatigue failure due to sharply-edged formation (corner, notch, small fillet radius, crevice, holes, craters) due to high hardness of surface and high stress cycles, surface and sub-surface defects with small radii, lead to stress concentrations and high Kt , Kf values leading to cracks
QUESTIONS
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the surface look like a fatigue failure
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Does your component have a keyway
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Has the component been cold worked?
ANSWER : Yes
Has the failure initiated within a thread run
ANSWER : Yes
Has spalling or delamination of the surface occurred

ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails, threads
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
What primary component group is your component
ANSWER : gears
Does the affected area have less strength than the parent material
ANSWER : No
ACTIONS
Increase the fatigue strength by surface treatment
Improve the manufacturing process and non-destructive testing
Remove surface and sub-surface defects to improve fatigue strength

BEGIN CASE CASE14
TITLE
Stress corrosion cracking in austenitic chromium nickel steels
DESCRIPTION : Failure by cracking under combined action of
corrosion and tensile stress, either external or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. In an Austenitic chromium nickel steels, S. C.C can occur in chlorine compounds
QUESTIONS
What is your primary material
ANSWER : Ni-Cr-Mo Steel
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl
Solutions, Seawater, Air, Water, Water Vapour
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : Yes
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
To stop stress corrosion cracking

BEGIN CASE CASE15
TITLE
Corrosion mechanical wear at corner, bends, junctions in pipes
DESCRIPTION : Corrosion mechanical wear at corner, bends
junctions in pipes due to turbulent flow at corner, bends change in sections. Turbulence causes localised rupture failure and corrosion.
increased by dispersed solids particles in flow (water, gas).
QUESTIONS
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
Would you consider the environment was corrosive in any way
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air
, Water, Water Vapour

Is there a source of hydrogen in the component environment
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Are two different metals touching each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
ACTIONS
Reduce mechanical wear and turbulence corrosion problems
Close or seal existing crevices
Reduce mechanical wear and turbulence erosion problems

BEGIN CASE CASE16
TITLE
Tensile shock overload failure on a carbon steel aircraft towing cable
DESCRIPTION : Tensile shock over load failure on a carbon steel (aircraft) towing cable. Shock loading increases at turns, stop, and starts, to increase stress past its tensile strength for material. Initial necking and unwinding of cable before failure
QUESTIONS
What primary component group is your component
ANSWER : Wire, Chain, or cable
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What level is the stress, (High, Low, or No load)
ANSWER : High
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air
, Water, Water Vapour
Does your component have a keyway
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Drawing, or Extrusion
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Does your component, have oil holes, grease nipples, etc
ANSWER : No
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : No
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
ACTIONS
Reduce shock loading in towing cables

BEGIN CASE CASE17
TITLE
Brittle cracks in steel due to low cycle fatigue from preexisting crack
DESCRIPTION : Brittle cracking in high hardness (bearing steel) steel due to Low-cycle fatigue from preexisting crack, caused by poor processing, over heating, as seen by surface defects, corrosion, erosion, surface remelting producing high surface hardness, transverse cracks due to quenching, poor electro-discharge machining EDM processing.
QUESTIONS

What is your primary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)
Does the surface look like a fatigue failure
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
What level is the stress, (High, Low, or No load)
ANSWER : High
What is the secondary process used in manufacture
ANSWER : Electro-discharge machining
What is the primary process used in manufacture
ANSWER : Machining
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
ACTIONS
Improve the manufacturing process and non-destructive testing
Improve electric discharge machining processing

BEGIN CASE CASE18
TITLE
Processing induced fatigue fracture in aluminum alloy component
DESCRIPTION : Processing-Induced fatigue fracture in Aluminum alloy component. Poor multiple plating, chemical etching, anodising, , can produce pits, pitting corrosion in surface are initiation sites for fatigue fracture. surface is flat, shiny, reflective facets, Baking can reduce mechanical strength
QUESTIONS
Does the surface look like a fatigue failure
ANSWER : Yes
What is your primary material
ANSWER : Aluminum alloy
What is your secondary material
ANSWER : Aluminium Alloys
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Has the component been electroplated,
ANSWER : Chemical etch and anodising
Has the component had a surface hardening treatment
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
ACTIONS
Processing-induced fatigue fracture in aluminum alloy component.
Increase the fatigue strength by surface treatment

BEGIN CASE CASE19
TITLE
Subsurface defect leading to fatigue failure in critically loaded part
DESCRIPTION : Subsurface defect leading to fatigue failure in critically loaded component Subsurface defect such as inclusions, voids, pores , precipitate, crack, manganese and ferrous sulphides, phosphorus, silicon oxides, segregations, etc, leading to fatigue failure in critically loaded component
QUESTIONS
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes

Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Is there any damage near to the possible fracture sites
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Are two different metals touching each other
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
ACTIONS
What to do for subsurface defects

BEGIN CASE CASE20
TITLE
Surface contact fatigue (pitting) failure of a gear
DESCRIPTION : Contact Fatigue failure of a bull gear, due to continual overloading of gear and a poor quality non-uniform case hardening
QUESTIONS
Does the surface look like a fatigue failure
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Does your component have a keyway
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
What primary component group is your component
ANSWER : gears
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
ACTIONS
To reduce excessive wear on a single gear or sprocket
Remedial action for case crushing failure

BEGIN CASE CASE21
TITLE
Overload failure in a sand cast aluminum base alloy
DESCRIPTION : Overload failure in a sand cast Aluminum-base alloy, this can be seen by extensive cracking and evidence of substantial deformation in the region around stress concentrations such as holes, corners keyways. Generally material (LM6) is in specification.
QUESTIONS
What is your primary material
ANSWER : Aluminum alloy
What is the primary process used in manufacture
ANSWER : Casting
What level is the stress, (High, Low, or No load)
ANSWER : High
What is the secondary process used in manufacture
ANSWER : Casting
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there extensive plastic deformation around the fracture site

ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Aluminium Alloys
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : No
ACTIONS
Overload failure in a sand cast aluminum-base alloy
Improve the manufacturing process and non-destructive testing. General overload failure prevention (& fatigue failure prevention)

BEGIN CASE CASE22
TITLE
General overload failure
DESCRIPTION : Overload failure in a material, can be seen by extensive cracking and evidence of substantial deformation in the region around stress concentrations such as holes, corners keyways.
Generally material is in specification and in good condition.
QUESTIONS
What level is the stress, (High, Low, or No load)
ANSWER : High
Has the failure occurred before the part went into service
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
If welding electrodes are used, have they been damaged
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : No
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does your component have a keyway
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
ACTIONS
General overload failure prevention (& fatigue failure prevention)
Improve the manufacturing process and non-destructive testing

BEGIN CASE CASE23
TITLE
Flow erosion in pipes
DESCRIPTION : Turbulent fast velocity flow in pipes can cause erosion leading to leakage. This could be in

a plastic, copper or an non-corroding material . Wear patterns show Wall thinning at areas of fast flow or turbulence (eddies), and deposit build up in areas of low flow with the reduction in mechanical properties. Welding bead protrusions on the pipe inside wall increase the problem.
QUESTIONS
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
What is the secondary process used in manufacture
ANSWER : Welding
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
Does your component have a keyway
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : Low
ACTIONS
Reduce mechanical wear and turbulence erosion problems
Reduce mechanical wear and turbulence corrosion problems

BEGIN CASE CASE24

TITLE
Stress corrosion cracking in 300 series stainless steel
DESCRIPTION : Failure by cracking under combined action of corrosion and tensile stress, either external stress or internal stress. Cracking may be transgranular or intergranular depending on metal and corrosive medium. Austenitic stainless steel 300 series undergo SCC when subjected to chloride solutions. Nuts and bolts increase the SCC due to the cracks, crevices and threads
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
What is your primary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
What are the primary environmental conditions
ANSWER : NaCl-K2CrO4 Solutions
Rural and coastal atmospheres
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air
, Water, Water Vapour
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations

Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
ACTIONS
To stop stress corrosion cracking

BEGIN CASE CASE25
TITLE
Impact spalling in steel
DESCRIPTION : Spalling is the cracking and flaking of particles out of a surface, caused by two surfaces (forge, rolling mill, hammering,) been together under a cyclic load in which the subsurface shear strength is inadequate to withstand the shear stress. The surface is generally harder than the core. Crack start, subsurface at inclusions where the contact stresses are maximised. Sliding action, (bearing or contact roller),may initiate crack at the surface, forming pits Linked to contact fatigue, pitting and high contact stresses.
QUESTIONS
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Has the component had a surface hardening treatment
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are two different metals touching each other
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
Has the failure initiated within a thread run
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : Low
ACTIONS
Spalling problems

BEGIN CASE CASE26
TITLE
Cracking on the parting line of closed die forgings
DESCRIPTION : Crack can occur at a parting line in a forging. These can grow during heat treatment. A large grain structure and high temperature scale can be seen around parting line, which is not normally seen in forged components. Associated with carbon and low alloy steel.
QUESTIONS
What is the primary process used in manufacture
ANSWER : Forging
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
What is the secondary process used in manufacture
ANSWER : Forging
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
What is your primary material
ANSWER : Ni-Cr-Mo Steel
Does the affected area have less strength than the parent material
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
What level is the stress, (High, Low, or No load)
ANSWER : High
Has the failure initiated within a thread run
ANSWER : No
What component group is NOT linked or like your component at all
ANSWER : pipes, tanks, & other fluid holding components

What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
ACTIONS
Cracking at a parting line in a forging.
Remove surface and sub-surface defects to improve fatigue strength
Increase the fatigue strength by surface treatment
Improve the manufacturing process and non-destructive testing

BEGIN CASE CASE27
TITLE
Creep failure of a superheated tube by graphitization / spheroidization
DESCRIPTION : Creep is a slow plastic deformation failure
dependent on materials, time, with temperature, and service stresses, which can be small and static. This would be seen as a longitudinal rupture or deformation near a bend. Graphitization /
spheroidization occurs in Carbon Molybdenum steels at temperatures above 420 C
QUESTIONS
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
What is the secondary process used in manufacture
ANSWER : Welding
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails
Does a gas flow around or through your component
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What component group is NOT linked or like your component at all
ANSWER : other
Has the failure initiated within a thread run
ANSWER : No
ACTIONS
Steel creep failures by graphitization / spheroidization
General creep failures in materials

BEGIN CASE CASE28
TITLE
Corrosion fatigue failure
DESCRIPTION : Corrosion Fatigue Failure is caused by a
combination of fluctuating stress and an aggressive environment (ph changes & higher temperatures) which proportionally increases crack growth and reduces fatigue life. Increasing the corrosive environment reduces the fatigue initiation stress
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Are there any sharp corners or sharp radii
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl
Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Room
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the affected area have less strength than the parent material
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes

ACTIONS
Corrosion fatigue
Close or seal existing crevices
General corrosion problems
Fatigue calculations

BEGIN CASE CASE29
TITLE
Ductile overload
DESCRIPTION : Ductile overload occurs in tension, bending, and torsion. Where the component undergoes plastic extension, then necking at a weakness and triaxial stresses are set up to produce a central crack and 45 degree lips (shear planes) at the edges. a dimpled central fracture and plastic deformation are signs of a ductile failure.
QUESTIONS
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the affected area have less strength than the parent material
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
ACTIONS
General overload failure prevention (& fatigue failure prevention)

BEGIN CASE CASE30
TITLE
Liquid metal embrittlement of copper alloys (Brass) by liquid metals
DESCRIPTION : Liquid-metal embrittlement is the brittle
intergranular failure with little indication of crack branching or striation to indicate slow crack propagation, of a normally ductile metal when coated with a thin film of liquid metal and stressed. Mercury especially, and also Antimony, Cadmium, Lead, Tin, Lithium, Sodium, Bismuth, Gallium, Indium, Thallium embrittles Copper, which increases when alloyed with Aluminum, and zinc (Brass)
QUESTIONS
What is your primary material
ANSWER : 70% Copper , 30% Zinc (Cartridge Brass)
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : Yes
SCORING : (-)
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Are two different metals touching each other
ANSWER : Yes
What is your secondary material
ANSWER : Copper alloys
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
ACTIONS

Liquid-metal embrittlement of steel or copper alloys by liquid metals

BEGIN CASE CASE31
TITLE
Liquid metal embrittlement (LME) of steel by liquid metals
DESCRIPTION : Liquid-metal embrittlement (LME) is a brittle intergranular failure with little crack branching or striation to indicate slow crack propagation, in a normally ductile metal when coated with a thin film of liquid metal and stressed. Crack growth is fast. Initiation occurs at solid-liquid metal interface. Steel is LMIE by Mercury, Gallium, Sodium, Indium, Lithium, Tin, Cadmium, Lead, Zinc, Antimony, Tellurium, Copper.
QUESTIONS
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What is your secondary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC)
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : Yes
SCORING : (-)
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Are two different metals touching each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
ACTIONS
Liquid-metal embrittlement of steel or copper alloys by liquid metals

BEGIN CASE CASE32
TITLE
Fracture of a cast component due to low strength & large grain sizes
DESCRIPTION : A low strength material with a large grain size undertaking a high load. Cyclic loads lead to fatigue failure. Plastic deformation and orange peel are features of this failure.
QUESTIONS
What is the primary process used in manufacture
ANSWER : Casting
What is the secondary process used in manufacture
ANSWER : Casting
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
ACTIONS
General overload failure prevention (& fatigue failure prevention)
Increase the strength of a given material

BEGIN CASE CASE33
TITLE
Hydrogen embrittlement failure of maraging steel bourdon tubes
DESCRIPTION : Cracking by Hydrogen embrittlement in maraging steel bourdon tubes. Processing involved bending tubes after filling with low melting alloy, which is then melted out. Incomplete removal of alloy occurring would lead to

dissimilar metal corrosion (pitting) in service, the cathodic half reaction being hydrogen evolution. Axial & circumferential (initiate from drill marks) crack possible.
QUESTIONS
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : Yes
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Are two different metals touching each other
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Casting
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : Yes
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
Hydrogen embrittlement failure of maraging steel bourdon tubes

BEGIN CASE CASE34
TITLE
Sulphide stress corrosion cracking
DESCRIPTION : Sulphide Stress (sour) Corrosion (brittle)Cracking occurs with oil & gas due to hydrogen sulphide gas, hydrogen sulphide, & water. More corrosive when moisture, oxygen and carbon dioxide are present. Seen as pitting corrosion & corrosion-erosion. Generally occurs in high strength materials with the application of external stresses. Increases at room temperature. Susceptible materials are
stainless steel & Nickel alloys
QUESTIONS
What is your primary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
What is your secondary material
ANSWER : Austenitic (Ni-Cr-Mo)
Stainless Steel (Face centred cubic, FCC)
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
What is the secondary process used in manufacture
ANSWER : Welding
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : Yes
What level is the stress, (High, Low, or No load)

ANSWER : High
What are the primary environmental conditions
ANSWER : Calcium, Ammonium, & Sodium Nitride solutions, Mixed acids
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What component group is NOT linked or like your component at all
ANSWER : Wire, Chain, cable or hooks
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Has the failure initiated within a thread run
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
ACTIONS
Sulphide stress (sour) corrosion cracking

BEGIN CASE CASE35
TITLE
Torsional fatigue failure of shafts
DESCRIPTION : Torsional Fatigue Failure of shafts can be seen by the star-formation on the fracture surface.
Typically the initiation starts at keyways, holes, splines and changes in cross section. Multiple initiations from each stress raiser are not
uncommon (splines). Cracks are at 45 to the shaft axis
QUESTIONS
What primary component group is your component
ANSWER : shafts, masts, poles, struts, rails, threads
What secondary component group is your component linked to
ANSWER : gears
What is the primary process used in manufacture
ANSWER : Machining
What is the secondary process used in manufacture
ANSWER : Forging
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Does your component have a keyway
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Does the surface look like a fatigue failure
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Are a non-metal and a metal in contact with each other
ANSWER : No
Are two different metals touching each other
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
What component group is NOT linked or like your component at all
ANSWER : pipes, tanks, & other fluid holding components
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : No
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a gas flow around or through your component
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : No
ACTIONS
Increase the fatigue strength by surface treatment
General overload failure prevention (& fatigue failure prevention)
Remove surface and sub-surface defects to improve fatigue strength

Improve the manufacturing process and non-destructive testing
Processing-induced fatigue fracture in aluminum alloy component.
Fatigue calculations

BEGIN CASE CASE36
TITLE
Excessive wear of a single sprocket or gear
DESCRIPTION : Excessive wear of a single sprocket or gear, by other sprockets or gears may be due to poor manufacture, or hard surfaces/particles in other sprockets/gears, as the failed gear is softer than the others. The surface is likely to look scratched, then scuffed, and finally scored with increased wear.
QUESTIONS
What primary component group is your component
ANSWER : gears
If your component is a gear or shaft, does it have splines
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Does a gas flow around or through your component
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Room
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
ACTIONS
To reduce excessive wear on a single gear or sprocket
Increase the strength of a given material
Reduce mechanical wear and turbulence erosion problems
Inspect and remove deposits frequently
Improve the manufacturing process and non-destructive testing

BEGIN CASE CASE37
TITLE
Adhesive wear of gears causing pits, welded particles & tooth failures
DESCRIPTION : Adhesive wear of gears occurs on sliding surfaces when the contact pressure causes plastic
deformation and adhesion. Surface glazing followed by galling then seizure and failure occurs. Galling is the adhesion of sliding surfaces which pull areas of material off one surface. So one surface has pits and the other has bumps. Broken teeth and total gear failure possible. Can be caused by other foreign objects
QUESTIONS
What primary component group is your component
ANSWER : gears
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes

If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : No
What secondary component group is your component linked to
ANSWER : Bearings
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
What level is the stress, (High, Low, or No load)
ANSWER : High
What component group is NOT linked or like your component at all
ANSWER : pipes, tanks, & other fluid holding components
ACTIONS
Adhesive wear

BEGIN CASE CASE38
TITLE
Internal stress rupture in a gear tooth
DESCRIPTION : When internal residual stresses build up to a point which exceeds the strength of the material, rupture will occur. The internal rupture of a gear is linked to the case core transition interface zone near the top face or the corner of the tooth
Separation of the case/core can remove the top of the tooth
QUESTIONS
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : gears
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Casting
What primary component group is your component
ANSWER : gears
Does the affected area have less strength than the parent material
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Does your component have a keyway
ANSWER : Yes
ACTIONS
Internal stress rupture of gears
What to do for subsurface defects
General overload failure prevention (& fatigue failure prevention)

BEGIN CASE CASE39
TITLE
External stress rupture in a gear not in service
DESCRIPTION : When the gear in not in service external stress rupture originates from a stress raiser and

residual stresses. This could be poor grinding, sharp notches, tooth undercutting. If residual stresses build up to a point which exceeds the strength of the material, rupture will occur at the stress raiser. The stress raiser is generally not the entire cause of the failure but provides the initiation point.
QUESTIONS
Has the failure occurred before the part went into service
ANSWER : Yes
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : High
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : gears
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Casting
What primary component group is your component
ANSWER : gears
Does the affected area have less strength than the parent material
ANSWER : No
ACTIONS
Stress concentration factors and how to reduce them
Internal stress rupture of gears
What to do for subsurface defects
General overload failure prevention (& fatigue failure prevention)

BEGIN CASE CASE40
TITLE
Tooth bending impact and shear failure of gears
DESCRIPTION : When a tooth is removed from the gear within a few cycles (one or two) with a uniform fracture with no striations, this is tooth-bending impact. Generally random failure due to shock loading and not just at root radius. Commonly in combination with "Tooth Shear"failures which are due to high stress & short time impacts with resultant failure by shear across the tooth to a convex shape.
QUESTIONS
What primary component group is your component
ANSWER : gears
Has the failure occurred before the part went into service
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
What level is the stress, (High, Low, or No load)
ANSWER : High
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Would you consider the environment was corrosive in any way

ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : gears
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Casting
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Does your component have a keyway
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
ACTIONS
Tooth-bending impact and shear failure of gears Stress concentration factors and how to reduce them General overload failure prevention (& fatigue failure prevention)

BEGIN CASE CASE41
TITLE
Tooth chipping of gears
DESCRIPTION : An impact failure, though not considered to be tooth-to-tooth impact, but an external force, such as a foreign object (Bolt, a broken tooth from another gear). Random chips, lumps, taken out of the gear, with a general brittle nature. However mishandling causes most chips
QUESTIONS
What primary component group is your component
ANSWER : gears
What secondary component group is your component linked to
ANSWER : gears
Has the failure occurred before the part went into service
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
What component group is NOT linked or like your component at all
ANSWER : spring
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Casting
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does your component have a keyway
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
ACTIONS
Tooth chipping of gears

BEGIN CASE CASE42
TITLE
Case crushing failure of a carburized case hardened component
DESCRIPTION : Case crushing will occur when a high load/stress is applied to a carburized case on a steel surface and this is linked to gear failures. May be seen as small surface cracks and subsurface defects. Depends on stress applied, radius of contact, thickness of carburized case and core hardness.
QUESTIONS
Has the component had a surface hardening treatment
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What is your secondary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC)
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : No
Does your component have a keyway
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : gears
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Casting
What primary component group is your component
ANSWER : gears
Does the affected area have less strength than the parent material
ANSWER : No
ACTIONS
Remedial action for case crushing failure
Spalling problems
General overload failure prevention (& fatigue failure prevention)
What to do for subsurface defects
Remove surface and sub-surface defects to improve fatigue strength
Increase the fatigue strength by surface treatment8/1/94

BEGIN CASE CASE43
TITLE
Thermal fatigue in gears
DESCRIPTION : Not necessarily correct, but its linked to
frictional heating. Found mostly on rotating faces of gears, that are exerting a high thrust, but also on active profiles of gears. Thermal expansion (heating) and contraction (cooling) initiates a large number of radial cracks and progress to fatigue cracks into the bore of gear and along the roots of the teeth.
QUESTIONS
Has the failure occurred before the part went into service
ANSWER : No
If your component is a gear or shaft, does it have splines
ANSWER : Yes
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC

ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : gears
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Casting
What primary component group is your component
ANSWER : gears
ACTIONS
Thermal fatigue in gears

BEGIN CASE CASE44
TITLE
General corrosion
DESCRIPTION : General Corrosion, involves uniform attack,
produces thinning of the material. Caused by incorrect material for the environment. Prevented by use of different corrosion-resistant material, a protective coating, or the use of cathodic protection.
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air
, Water, Water Vapour
What are the primary environmental conditions
ANSWER : Rural and coastal atmospheres
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Are two different metals touching each other
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : No Load
ACTIONS
General corrosion problems

BEGIN CASE CASE45
TITLE
Galvanic corrosion
DESCRIPTION : Occurs when dissimilar metals are in contact with each other in a conductive solution (electrolyte) Corrosion rate increases when metal are far apart in galvanic series and more aggressive environments. Also when anode (Corroded metal) is smaller than cathode.
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes

Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
ACTIONS
Galvanic corrosion

BEGIN CASE CASE46
TITLE
Crevice corrosion
DESCRIPTION : Crevice Corrosion occurs at bolted & locknut joints, junctions, cracks, poor quality welds or under deposits between metal and or non-metals allowing concentrations of corrosive species, particularly chloride ions to be generated within a crevice or stagnant area.
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
Has the failure initiated within a thread run
ANSWER : Yes
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
What is the secondary process used in manufacture
ANSWER : Machining
What is the primary process used in manufacture
ANSWER : Welding
What primary component group is your component
ANSWER : Mechanical Fastenings (Rivets, Nuts & Bolts)
ACTIONS
Crevice corrosion
Stainless Steel Engineering Guide (Nickel Development Institute)

BEGIN CASE CASE47
TITLE
Pitting corrosion
DESCRIPTION : Pitting Corrosion similar to crevice corrosion but localized around small pits or cavities on a metal surface due to differences in oxygen and ion concentrations at base of pit which becomes anodic, compared to the surrounding metal which atmospheric oxygen can diffuse. Found commonly in the presence of chloride ions.
QUESTIONS
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No

Are there any sharp corners or sharp radii
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What secondary component group is your component linked to
ANSWER : welded components
Did the failure occur at room or a higher temperature
ANSWER : Room
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : No Load
ACTIONS
Pitting corrosion
General corrosion problems

BEGIN CASE CASE48
TITLE
Intergranular corrosion
DESCRIPTION : Intergranular Corrosion involves preferential dissolution of grain boundary phases or adjacent zones, due to the formation of an anode because of the precipitation of a second phase. Occurs in many materials, i.e. stainless steel, Aluminum and nickel alloys
QUESTIONS
Would you consider the environment was corrosive in any way
ANSWER : Yes
What is your primary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC)
Does the surface look like a fatigue failure
ANSWER : No
What is your secondary material
ANSWER : Aluminum alloy
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Has the failure initiated within a thread run
ANSWER : Yes
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Did the failure occur at room or a higher temperature
ANSWER : Above 0.6 of the melting temperature
What is the secondary process used in manufacture
ANSWER : Casting
What is the primary process used in manufacture
ANSWER : Welding
ACTIONS
Intergranular Corrosion
General corrosion problems
Stainless Steel Engineering Guide (Nickel Development Institute)

BEGIN CASE CASE49
TITLE
Dezincification and denickelification
DESCRIPTION : Dezincification is a selective leaching process in brass, whereby zinc dissolves and a brittle low strength spongy porous copper deposit remains. In Copper-nickel alloys, nickel is leached out, (denickelification). Linked to exposure in fresh or sea water with boats, shipping, nuts, bolts, pipes, etc and heat exchangers. Can occur after exposure to fresh or sea water, brass develops copper-coloured layers or plugs of material.
QUESTIONS
What is your primary material
ANSWER : Copper alloys (e.g. 70% Copper , 30% Zinc,
Cartridge Brass or Aluminum)
What is your secondary material
ANSWER : Copper alloys
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Would you consider the environment was corrosive in any way
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle

Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
What component group is NOT linked or like your component at all
ANSWER : spring
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
What primary component group is your component
ANSWER : Mechanical Fastenings (Rivets, Nuts & Bolts)
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Are there any cracks perpendicular to the tensile stress
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : No Load
ACTIONS
Dezincification and denicklification

BEGIN CASE CASE50
TITLE
Sulphide stress corrosion cracking in pipe lines
DESCRIPTION : Brittle failure in a high-strength steel by cracking under the combined action of tensile stress and a corrosive environment of water and hydrogen sulphide, (H2S). Cathodic corrosion process. Sulphide Stress (sour) Corrosion (brittle) Cracking occurs with oil & gas due to hydrogen sulphide gas, hydrogen sulphide, & water. More corrosive when moisture, oxygen and carbon dioxide are present. Seen as pitting corrosion & corrosion- erosion. Generally occurs in high strength materials with the application of external stresses. Increases at room temperature. Susceptible
materials are stainless steel & Nickel alloys
QUESTIONS
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
Did the failure occur at room or a higher temperature
ANSWER : Below room temp possible freezing
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
What is the secondary process used in manufacture
ANSWER : Welding
What level is the stress, (High, Low, or No load)
ANSWER : Low
Does the affected area have less strength than the parent material
ANSWER : Yes
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
Would you consider the environmental pH to be either:

ANSWER : High, e.g. Alkaline
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl
Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Has the component been cold worked?
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What component group is NOT linked or like your component at all
ANSWER : spring
Has the component had a surface hardening treatment
ANSWER : Yes
ACTIONS
Sulphide stress (sour) corrosion cracking

BEGIN CASE CASE51
TITLE
Hydrogen pressure cracking in pipe lines
DESCRIPTION : Brittle failure in a lower-strength line pipe steel (>550 MPa) by cracking along the rolling plane under the combined action of tensile stress and a corrosive environment of water and hydrogen
sulphide, (H2S). Cathodic corrosion process, associated with non-metallic inclusions (manganese and calcium sulphides also bands of hard transformation products in low strength materials). Seen as blisters, straight and step cracking.
QUESTIONS
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
Does the affected area have less strength than the parent material
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl
Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : Low
Has the component been cold worked?
ANSWER : Yes
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What component group is NOT linked or like your component at all
ANSWER : spring
ACTIONS
Hydrogen-Damage failures
Hydrogen embrittlement failure of maraging steel bourdon tubes

BEGIN CASE CASE52
TITLE

Decarburisation of steel
DESCRIPTION : Decarburisation occurs at high temperature with hydrogen or oxidizing atmosphere or chemical
substance, which reacts with carbon in steel alloys to reduce the carbon from the surface layer causing loss of fatigue and tensile strength
QUESTIONS
What is your primary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic,
FCC)
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Did the failure occur at room or a higher temperature
ANSWER : Above 0.6 of the melting temperature
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Has the failure occurred before the part went into service
ANSWER : Yes
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Is there a source of hydrogen in the component environment
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water
Vapour
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Has the failure initiated within a thread run
ANSWER : No
What secondary component group is your component linked to
ANSWER : welded components
What is the secondary process used in manufacture
ANSWER : Forging
What is the primary process used in manufacture
ANSWER : Casting
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile

BEGIN CASE CASE53
TITLE
Micro biological corrosion
DESCRIPTION : Bio-Fouling and Bacterial corrosion in marine, oil fields, aluminum jet fuel cells, and sewage pipe environments are caused by anaerobic & aerobic bacteria, fungus, and macro-organisms (barnacles, mussels, etc) change air, oxygen, and pH levels to acid, through reduction or oxidation of sulphur compounds and the suppression of cathodic reactions.
QUESTIONS
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
Would you consider the environment was corrosive in any way
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc

ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are a non-metal and a metal in contact with each other
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : Rural and coastal atmospheres
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
ACTIONS
Microbiological Corrosion
General corrosion problems

BEGIN CASE CASE54
TITLE
Temper embrittlements (Ductile to brittle transition type fractures)
DESCRIPTION : Low-alloy steel that are either cooled slowly through 600 to 350 C or prolonged exposure to that range could be subjected to intergranular failure accompanied by a large increase in ductile to brittle transition temperature. Mostly occur in body cantered cubic structures (non-austenitic steel) at low temperatures.
QUESTIONS
Did the failure occur at room or a higher temperature
ANSWER : Above 0.6 of the melting temperature
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Does the affected area have less strength than the parent material
ANSWER : Yes
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Has the failure occurred before the part went into service
ANSWER : No
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : Low
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Are two different metals touching each other
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
ACTIONS
Brittle fracture of a rail arising from flame- cutting

BEGIN CASE CASE55
TITLE
Radiation embrittlements (Ductile to brittle transition type fractures)
DESCRIPTION : Neutron embrittlement. Irradiation of Low-alloy steel could cause large increase in ductile to brittle transition temperature and be subjected to an intergranular failure. Mostly occur in body cantered cubic structures (non-austenitic steel) at low temperatures. X-ray, gamma, heavy-particle radiation or fission fragments in nuclear fuel also alter material properties
QUESTIONS

Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : Yes
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Are two different metals touching each other
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : No
What is your primary material
ANSWER : Carbon Steels, (Body
centred cubic, BCC)
What level is the stress, (High, Low, or No load)
ANSWER : Low
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
Is there a source of hydrogen in the component environment
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
ACTIONS
Fatigue fracture due to abrupt thread run-out
Neutron Embrittlement

BEGIN CASE CASE56
TITLE
Caustic cracking due to poor rivetted seams in a steel ships' boiler
DESCRIPTION : Poor rivetted seams leave cracks & crevices for water to collect and evaporate thus concentrating the levels of sodium carbonate (sodium hydroxide). Possible white crystalline
deposits seen indicate caustic alkali. Similar to stress corrosion cracking. Occurs in steels (iron & iron-chromium-nickel alloys)
QUESTIONS
What primary component group is your component
ANSWER : Mechanical Fastenings (Rivets, Nuts & Bolts)
What is the primary process used in manufacture
ANSWER : Rivetted seam
What is the secondary process used in manufacture
ANSWER : Rivetted seam
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
What component group is NOT linked or like your component at all
ANSWER : spring
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Austenitic (Ni-Cr-Mo)
Stainless Steel (Face centred cubic, FCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle

Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What level is the stress, (High, Low, or No load)
ANSWER : High
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Does your component have a keyway
ANSWER : No
ACTIONS
Caustic cracking due to poor rivetted seams in a steel ships boiler
Caustic Cracking

BEGIN CASE CASE57
TITLE
Brittle fracture of a rail arising from flame- cutting
DESCRIPTION : Brittle fracture of a rail arising from flame- cutting of slots. Crack originate from corners and the hard martensitic structured surface layer caused by the rapid heating and cooling into the large cold rail mass.
QUESTIONS
What is the primary process used in manufacture
ANSWER : Flame cutting
What primary component group is your component
ANSWER : shafts, masts, poles, struts, rails
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Does the affected area have less strength than the parent material
ANSWER : Yes
What is your secondary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Does your component have a keyway
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two different metals touching each other
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
What is the secondary process used in manufacture
ANSWER : Welding
Has the component been electroplated,
ANSWER : No electroplating
What level is the stress, (High, Low, or No load)
ANSWER : Low
Did the failure occur at room or a higher temperature
ANSWER : Room
Has the failure occurred before the part went into service
ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
If welding electrodes are used, have they been damaged
ANSWER : Yes

Does your component, have oil holes, grease nipples, etc
ANSWER : No
ACTIONS
Brittle fracture of a rail arising from flame- cutting

BEGIN CASE CASE58
TITLE
Fatigue fracture due to abrupt thread run-out
DESCRIPTION : Fatigue fracture due to abrupt thread run-out occurs at localities where there are high bending stresses as in lifting swivelling shackles, and nut and thrust-race combinations.
Fatigue cracks initiate at the root of the last thread and propagate in the direction of stress
QUESTIONS
What primary component group is your component
ANSWER : Mechanical Fastenings (Rivets, Nuts & Bolts)
Has the failure initiated within a thread run
ANSWER : Yes
What is the primary process used in manufacture
ANSWER : Machining
What secondary component group is your component linked to
ANSWER : Mechanical Fastenings (Rivets, Nuts & Bolts)
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What is the secondary process used in manufacture
ANSWER : Machining
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What level is the stress, (High, Low, or No load)
ANSWER : High
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Did the failure occur at room or a higher temperature
ANSWER : Room
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
What component group is NOT linked or like your component at all
ANSWER : spring
Does your component, have oil holes, grease nipples, etc
ANSWER : No
Does your component have a keyway
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : Yes
ACTIONS
Fatigue fracture due to abrupt thread run-out
11/7/94 19:53:7

BEGIN CASE CASE59
TITLE
Corrosion fatigue of overlay welded shaft on a ferry stabiliser fin
DESCRIPTION : Fatigue cracks originated at overlay welded shaft on a ferry stabiliser fin (welded by Fleet fusion process with Inconel 625, 1mm thick on BS970 steel) & propagated inwards for 13% of stock before failure, under bending loading conditions in sea water, which due to corrosion reduced fatigue strength.
EM/1538/90

QUESTIONS
What is your primary material
ANSWER : Overlay welded steel for corrosion and wear resistance
What primary component group is your component
ANSWER : shafts, masts, poles, struts, rails
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails
What is the primary process used in manufacture
ANSWER : Welding
What is the secondary process used in manufacture
ANSWER : Welding
Did the failure occur at room or a higher temperature
ANSWER : Room
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Are two different metals touching each other
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : Rural and coastal atmospheres
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
What component group is NOT linked or like your component at all
ANSWER : spring
Does your component have a keyway
ANSWER : No
ACTIONS
Corrosion Fatigue of overlay welded shaft on a ferry stabiliser fin
Corrosion fatigue
General overload failure prevention (& fatigue failure prevention)
Increase the fatigue strength by surface treatment
Improve your welding procedure
BROWSE GRAPHIC, TOOLBOOK
BOOK : ferry PAGE : c:\cbrx13dk
BEGIN CASE CASE61
TITLE
Brittle fracture due to strain age embrittlement in a mild steel hook
DESCRIPTION : The hook conformed to B.S.482, & used in an
overhead hoist in a foundry. Failure was initiated at pre-existing crack defect, due to poor
manufacture. Then exposure to radiant heat from molten metal and being plastically strained would lead to strain-age embrittlement. Thus a ductile material would become brittle & notch sensitive. British engine boiler & electrical insurance
technical report 1965, Vol.VI, pp81-87
QUESTIONS
What primary component group is your component
ANSWER : Wire, Chain, cable or hooks
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit

What level is the stress, (High, Low, or No load)
ANSWER : High
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
What is the primary process used in manufacture
ANSWER : Forging
Are there any sharp corners or sharp radii
ANSWER : Yes
What is the secondary process used in manufacture
ANSWER : Casting
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Is there any damage near to the possible fracture sites
ANSWER : Yes
ACTIONS
Strain-age Embrittlement
General overload failure prevention (& fatigue failure prevention)
What to do for subsurface defects
Remove surface and sub-surface defects to improve fatigue strength
Increase the fatigue strength by surface treatment
Improve the manufacturing process and non-destructive testing

BEGIN CASE CASE63
TITLE
Hydrogen embrittlement
DESCRIPTION : Hydrogen embrittlement cracking occurs in high strength steels (Quench + tempered, Precipitation hardened) at ambient (room) temperatures. Seen as brittle (quasi) cleavage intergranular or
transgranular fractures with little plastic deformation. H2 cracking increases with strength from 690 MPa and with decreases in strain rate. Does not occur above 200 C
QUESTIONS
Is there a source of hydrogen in the component environment
ANSWER : Yes
What is the primary process used in manufacture
ANSWER : Welding
Does the affected area have less strength than the parent material
ANSWER : Yes
What is your primary material
ANSWER : Austenitic (Ni-Cr-Mo) Stainless Steel (Face centred cubic, FCC)
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
What is the secondary process used in manufacture
ANSWER : Flame cutting
Has the component been electroplated,
ANSWER : Cadmium plated
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Did the failure occur at room or a higher temperature
ANSWER : Room
Has the failure occurred before the part went into service
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : No Load
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Does your component, have oil holes, grease nipples, etc
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects

ANSWER : Yes
If welding electrodes are used, have they been damaged
ANSWER : No
Is there any damage near to the possible fracture sites
ANSWER : Yes
What primary component group is your component
ANSWER : other
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : No
Are two different metals touching each other
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
ACTIONS
Hydrogen-Damage failures

BEGIN CASE CASE64
TITLE
Hydrogen induced blistering
DESCRIPTION : Hydrogen induced blistering occurs in low strength alloys (steels) in corrosive & stress environments e.g. oil, petroleum, sour gas, propane pipelines where sour hydrogen sulphide hydrocarbon are
present. Also in acid pickling and on steel cathodes for electrolysis plating. It requires inclusions (manganese sulphates), precipitates, or martensite bands to be present.
QUESTIONS
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Carbon
Steels, (Body centred cubic, BCC)
Is there a source of hydrogen in the component environment
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
What are the primary environmental conditions
ANSWER : Hydrofluoric acid, Hydrofluosilicic acid
Has the component been electroplated,
ANSWER : Chemical etch and anodising
What level is the stress, (High, Low, or No load)
ANSWER : Low
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Did the failure occur at room or a higher temperature
ANSWER : Below room temp possible freezing

Does the affected area have less strength than the parent material
ANSWER : Yes
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
ACTIONS
Hydrogen-Damage failures

BEGIN CASE CASE65
TITLE
Cracking from precipitation of internal hydrogen, (Fish-eyes)
DESCRIPTION : Also called Fish-eyes (under bead cracking in
welding). Occurs in steel forgings at temperatures below 200 C in the form of small elliptical bright cracks (flakes). If welding is involved then under bead crack can occur in heat affected zone (HAZ) that can occur hours or days later
QUESTIONS

What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What is the primary process used in manufacture
ANSWER : Welding
What is the secondary process used in manufacture
ANSWER : Welding
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Are there any sharp corners or sharp radii
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Did the failure occur at room or a higher temperature
ANSWER : Room
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
ACTIONS
Hydrogen-Damage failures

BEGIN CASE CASE66
TITLE
Hydrogen attack
DESCRIPTION : Hydrogen attack, occurs at elevated temperatures, where the Hydrogen reacts with the substrate especially in petrochemical plants (oil, gas) at high pressure areas. Unaffected for days/months then a sudden loss of strength & ductility. Decarburisation of iron carbides to produce fissuring containing methane at grain boundaries. Effects copper and silver as well
QUESTIONS
Did the failure occur at room or a higher temperature
ANSWER : Above 0.6 of the melting temperature

Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : Yes
What is your secondary material
ANSWER : Copper alloys
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are a non-metal and a metal in contact with each other
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What level is the stress, (High, Low, or No load)
ANSWER : Low
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
What is the secondary process used in manufacture
ANSWER : Welding
ACTIONS
Hydrogen-Damage failures

BEGIN CASE CASE67
TITLE
Hydrogen cracking from hydride formation (Titanium)
DESCRIPTION : This occurs in Transition, rare earth, alkaline earth metals & also in Titanium, Tantalum,

Zirconium, Uranium, Thorium & their alloys. It causes increased strength but losses in ductility and toughness. Welding & melting picks up Hydrogen for hydride particle formation on cooling to give platelets with preferred orientation to parent lattice but with volume change
QUESTIONS
Did the failure occur at room or a higher temperature
ANSWER : Room
What is the secondary process used in manufacture
ANSWER : Casting
What is the primary process used in manufacture
ANSWER : Welding
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : Yes
What is your secondary material
ANSWER : Titanium alloys
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
What is your primary material
ANSWER : Titanium, Tantalum, Zirconium, Transition & rare earth metals
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
ACTIONS
Hydrogen-Damage failures
Hydrogen embrittlement failure of maraging steel bourdon tubes

BEGIN CASE CASE68
TITLE
Impeller failure due to repair or built up welds with pores
DESCRIPTION : A Cr Ni Mo steel impeller (propeller) suffered failure after 170 hrs service, @ 720 rpm, = to 7.3 x 10E6 stress reversals with cracks around impeller root areas Hardness was 284 HV (10kg). Surface was consistent with high cycle fatigue under conditions of bending stresses. The fatigue origin was a large sub-surface pore. It had been repaired/built up by welding containing pores. EM/ 1613/90
QUESTIONS
What is the primary process used in manufacture
ANSWER : Casting
What level is the stress, (High, Low, or No load)
ANSWER : High
What is your primary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)
What is the secondary process used in manufacture
ANSWER : Welding
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Did the failure occur at room or a higher temperature
ANSWER : Room
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the affected area have less strength than the parent material
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are a non-metal and a metal in contact with each other

ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are two different metals touching each other
ANSWER : No
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Are two metals either in close proximity to each other or touching
ANSWER : No
If welding electrodes are used, have they been damaged
ANSWER : Yes
What primary component group is your component
ANSWER : other
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails, threads
Does your component, have oil holes, grease nipples, etc
ANSWER : No
ACTIONS
Impeller failure due to a repair or built up weld with pores
BROWSE GRAPHIC, TOOLBOOK
BOOK : seacat1PAGE : c\cbrx13dk

BEGIN CASE CASE70
TITLE
Delamination & longitudinal split in extruded aluminium alloy mast
DESCRIPTION : BS 1474 6061 Aluminium alloy mast delaminated & split longitudinal due to poor extrusion, seen as extremely coarse grains due to slow cooling rate. Also dross, piping defects, & back-end defects lead to delaminations & areas of high friction - poor flow, produce oxide accumulation thus lead to poor welded joints, thus longitudinal splits
EM/1547/90QUESTIONS
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
What primary component group is your component
ANSWER : shafts, masts, poles, struts
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails
What is your primary material
ANSWER : Aluminum alloy
What is your secondary material
ANSWER : Aluminum alloy
What is the primary process used in manufacture
ANSWER : Extrusion
What is the secondary process used in manufacture
ANSWER : Welding
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : Rural and coastal atmospheres
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High

Did the failure occur at room or a higher temperature
ANSWER : Room
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into many parts, shattered, multiple failures
What component group is NOT linked or like your component at all
ANSWER : gears
ACTIONS
Delamination & longitudinal split in extruded aluminium alloy mast

BEGIN CASE CASE73
TITLE
Ductile flat face tensile fracture
DESCRIPTION : Occurs in ductile materials by triaxial tensile stresses. fracture plane is normal to the largest tensile stress. Necking precedes fracture & ends by shear lips that extends to the free surface. Area ratio of flat face fracture to shear lip increases with section thickness. examination will reveal equiaxed dimples formed by microvoid coalescence.
QUESTIONS
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Has the component had a surface hardening treatmcnt
ANSWER : No
ACTIONS
General overload failure prevention (& fatigue failure prevention)
Ductile failures

BEGIN CASE CASE74
TITLE
Ductile shear face tensile fracture
DESCRIPTION : Occur in ductile materials under plane stress conditions in thin walled sections or near free surfaces with or without necking, and at 45 angles to surface in steel fracture surface are fine silky gray, and faintly visible Necking in threaded areas (bolt). examination reveals elongated dimples with their long axis in the direction of the shear force. Pointing in the opposite directions on the mating fracture surfaces.
QUESTIONS
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Are there any cracks perpendicular to the tensile stress
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are there any sharp corners or sharp radii
ANSWER : Yes
Are a non-metal and a metal in contact with each other
ANSWER : No

Would you consider the environment was corrosive in any way
ANSWER : No
Has the component been electroplated,
ANSWER : No electroplating
ACTIONS
Ductile failures
General overload failure prevention (& fatigue failure prevention)

BEGIN CASE CASE75
TITLE
Fretting fatigue
DESCRIPTION : BROWSE GRAPHIC, TOOLBOOK
BOOK : run PAGE : c:\data\html_fil\fretting.htm

BEGIN CASE CASE76
TITLE
Buckling failure
DESCRIPTION : If an eccentric point load is applied to a beam, post or column under a high magnitude compressive load, excessive deflection occurs. Generally in combination with bending and typically seen in supports and ladders.
QUESTIONS
What primary component group is your component
ANSWER : shafts, masts, poles, struts, rails, threads
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What component group is NOT linked or like your component at all
ANSWER : Bearings
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Ductile
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : Yes
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : No
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
Buckling failures
BROWSE GRAPHIC, TOOLBOOK
BOOK : run PAGE : \html_fil\buckling.htm

BEGIN CASE CASE77
TITLE
Brinnelling failure
DESCRIPTION : When the static force or load between two curved surfaces in contact results in local permanent plastic yielding. Ball bearing race can become brinnelled leading to increased vibration, noise, and heating.
QUESTIONS
What primary component group is your component
ANSWER : Bearings
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What component group is NOT linked or like your component at all
ANSWER : pipes, tanks, & other fluid holding components
What secondary component group is your component linked to
ANSWER : gears
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : Yes
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Are two different metals touching each other

ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
Brinnelling Failure
BROWSE GRAPHIC, TOOLBOOK
BOOK : run PAGE : \html_fil\brinnell.htm

BEGIN CASE CASE80
TITLE
Gaseous corrosion in 300 series stainless steel
DESCRIPTION : Gaseous corrosion in stainless steel is due to a nitrogen atmosphere (HCl, Cl2) and the presence of hot gases (e.g: combustion gases). A high percentage of nickel is necessary to guard against gaseous corrosion, e.g. 600 series nickel superalloy.
QUESTIONS
Has the component been cold worked?
ANSWER : Yes
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
Did the failure occur at room or a higher temperature
ANSWER : Above the materials high temp. limit
What is the secondary process used in manufacture
ANSWER : Forging
What is the primary process used in manufacture
ANSWER : Extrusion, or Drawing
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Steady
Would you consider the environment was corrosive in any way
ANSWER : Yes
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
What is your primary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)
What level is the stress, (High, Low, or No load)
ANSWER : No Load
ACTIONS
Use a 600-series nickel-base superalloy

BEGIN CASE CASE81
TITLE
Internal cracks in cast steel 9% Ni
DESCRIPTION : Internal cracks that occur in Ni steel castings originate at austenitic grain boundaries that coincide with primary dendrite interfaces. The decrease of grain boundary cohesion arises from sulphur segregation. The addition of molybdenum is remarkably effective for preventing internal cracks.
QUESTIONS

Has the component been cold worked?
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
What is the primary process used in manufacture
ANSWER : Casting
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : Yes
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Is the stress above the threshold stress intensity factor for SCC
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : No
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : Yes
Does a gas flow around or through your component
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : No
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : No
Is there a source of hydrogen in the component environment
ANSWER : No
What is your primary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC)
What level is the stress, (High, Low, or No load)
ANSWER : No Load
Has the failure initiated within a thread run
ANSWER : No
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components

ACTIONS
What to do for subsurface defects

BEGIN CASE CASE82
TITLE
Electrostatic discharge attack on a thrust bearing
DESCRIPTION : Electrostatic discharge attack is caused by stray electrical currents. Such currents may result from residual magnetism. The presence of corrosive material, such as sulfides, contribute to failure by introducing unwanted deposits. Arcing damage also possible. Common in ship, boats, and liners propellor bearing using electrical cathodic corrosion protection.
QUESTIONS
Has spalling or delamination of the surface occurred
ANSWER : Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Surface damage, and deformations
What secondary component group is your component linked to
ANSWER : shafts, masts, poles, struts, rails, threads
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
What is the secondary process used in manufacture
ANSWER : Surface hardening treatment
What is the primary process used in manufacture
ANSWER : Machining
What primary component group is your component
ANSWER : Bearings
Does the affected area have less strength than the parent material
ANSWER : Yes
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Stainless Steels, Duplex, Austenitic (Face centred cubic, FCC),
Would you consider your material to be in a brittle or ductile state
ANSWER : Ductile
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Does a gas flow around or through your component
ANSWER : Yes
Has the component had a surface hardening treatment
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : No
Are two different metals touching each other

ANSWER : Yes
Are two metals either in close proximity to each other or touching
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : Yes
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : No
What is your primary material
ANSWER : Copper alloys (Brass (Zn) (Bronze, (Al,Sn,Si,ZnSi,Be,Ni,NiZn)
What level is the stress, (High, Low, or No load)
ANSWER : High
ACTIONS
Eliminate residual magnetism

BEGIN CASE CASE83
TITLE
Impact failure induced by water hammer on a welded pipe
DESCRIPTION : A welded pipe failed because of an impact induced by water hammer. This brittle failure is also the result of a combination of poor notch toughness and high stresses in the welded joint area.
QUESTIONS
Has the component been cold worked?
ANSWER : No
Has the failure initiated within a thread run
ANSWER : No
Has spalling or delamination of the surface occurred
ANSWER : No Spalling or delamination has occurred on the surface
Is the failure just surface damage or has it broken into parts
ANSWER : Broken into two parts,
What secondary component group is your component linked to
ANSWER : pipes, tanks, & other fluid holding components
Did the failure occur at room or a higher temperature
ANSWER : Room temperature
What is the secondary process used in manufacture
ANSWER : Forging
What is the primary process used in manufacture
ANSWER : Welding
What primary component group is your component
ANSWER : pipes, tanks, & other fluid holding components
Has the component been neutron irradiated (nuclear reactors, etc)
ANSWER : No
Is there a covering of bacteria, fungus, or macro-organisms
ANSWER : No
Does the affected area have less strength than the parent material
ANSWER : No
Has the failure occurred before the part went into service
ANSWER : No
What is your secondary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
Would you consider your material to be in a brittle or ductile state
ANSWER : Brittle
Has the failure occurred by a brittle or a ductile fracture
ANSWER : Brittle
Is there a liquid metal-solid metal interface (eg Hg and Cu alloy)
ANSWER : No
Does a liquid flow past, through, around, or next to your component
ANSWER : Yes
Does the surface look like a fatigue failure
ANSWER : No
Is there extensive plastic deformation around the fracture site
ANSWER : No
Does your component, have oil holes, grease nipples, etc
ANSWER : No
If the fracture surface is examined are there any subsurface defects
ANSWER : No
Has the component had a surface hardening treatment
ANSWER : No
Before failure was the surface in good condition, free from any initial defects
ANSWER : Yes
Of any stress imposed whatever level, it is steady or fluctuating
ANSWER : Fluctuating
Would you consider the environment was corrosive in any way
ANSWER : No
Are there any other possible secondary solutions in the environment
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
What are the primary environmental conditions
ANSWER : NaCl-H2O2, NaCl Solutions, Seawater, Air, Water, Water Vapour
Are there any cracks perpendicular to the tensile stress
ANSWER : Yes
Is there any damage near to the possible fracture sites
ANSWER : Yes
Is there a source of hydrogen in the component environment
ANSWER : Yes
What is your primary material
ANSWER : Carbon Steels, (Body centred cubic, BCC)
What level is the stress, (High, Low, or No load)

ANSWER : High
What component group is NOT linked or like your component at all
ANSWER : gears
ACTIONS
Impact failure induced by water hammer on a welded pipe

Appendix 2. Complete Programming Listing of the Rules

```
//This is a list of rules that is used in the jasp3.
//Expert system
//The first set are linked to the automatic answering of
//questions
//from the description given in the initial natural
language
//description.

//question on the primary materials Question 4
0 "steel"
=>
4 "Carbon Steels, (Body centred cubic, BCC)"
;

0 "stainless"
=>
4 "Stainless Steels, Duplex, Austenitic (Face centred
cubic, FCC)"
;

0 "aluminium"
=>
4 "Aluminum alloys"
;

0 " al alloy"
=>
4 "Aluminum alloys"
;

0 "gold"
=>
4 "gold alloys"
;

0 "copper"
=>
4 "Copper alloys (Brass (Zn) (Bronze,
(Al,Sn,Si,ZnSi,Be,Ni,NiZn)"
;

0 "brass"
=>
4 "Copper alloys (Brass (Zn) (Bronze,
(Al,Sn,Si,ZnSi,Be,Ni,NiZn)"
;

0 "bronze"
=>
4 "Copper alloys (Brass (Zn) (Bronze,
(Al,Sn,Si,ZnSi,Be,Ni,NiZn)"
;

0 "titanium"
=>
4 "Titanium, Tantalum, Zirconium, Transition & rare
earth metals"
;

0 "tantalum"
=>
4 "Titanium, Tantalum, Zirconium, Transition & rare
earth metals"
;

0 "zirconium"
=>
4 "Titanium, Tantalum, Zirconium, Transition & rare
earth metals"
;
0 "earth metal"
=>
4 "Titanium, Tantalum, Zirconium, Transition & rare
earth metals"
;
0 "overlay weld"
=>
4 "Overlay welded steel for corrosion and wear
resistance"
;

//Questions relating to electroplating of materials
//(Hard chromium plating,
//Chemical etch and anodising, No electroplating,
//Cadmium plated) Question 6

0 "plating"
=>
6 "Hard chromium plating"
;

0 "anodi"
=>
6 "Chemical etch and anodising"
;

0 "cadmium"
=>
6 "Cadmium plated"
;

//Questions related to sources of hydrogen Question 9

0 "H2"
=>
9 "Yes"
;

0 "hydro"
=>
9 "Yes"
```

```
;

0 "water"
=>
9 "Yes"
;

//Question related to Corrosion question 15

0 "corro"
=>
15 "Yes"
;

//Question related to the steady or
//fluctuation stress Question 16
0 "steady"
=>
15 "steady"
;
0 "cycli"
=>
15 "Fluctuating"
;
0 "fluctuat"
=>
15 "Fluctuating"
;

//Question related to sharp corners or
// sharp radii Question 21
0 "keyway"
=>
21 "Yes"
;

0 "groove"
=>
21 "Yes"
;
0 "channel"
=>
21 "Yes"
;

0 "cavit"
=>
21 "Yes"
;

0 "abrupt"
=>
21 "Yes"
;

//Question relates to whether or
// not there is a keyways Question
26
0 "keyway"
=>
26 "Yes"
;

//Question relates to whether or
// not the component had a surface
//hardening treatment
// Question 27

0 "quench"
=>
27 "Yes"
;

0 "carburi"
=>
27 "Yes"
;
0 "carbonit"
=>
27 "Yes"
;

0 "Nitriding"
=>
27 "Yes"
;

0 "age hard"
=>
27 "Yes"
;

0 " anodi"
=>
27 "Yes"
;

0 "surface"
0 "hardening"
=>
27 "Yes"
;

//Question relates to gas flows question 28

0 " gas"
=>
28 "Yes"
;

//Question related to subsurface defects Question 30

0 "phosph"
=>
30 "Yes"
;

0 "blowhole"
=>
30 "Yes"
```

```
;

0 "spong"
=>
30 "Yes"
;

0 "non-metallic"
=>
30 "Yes"
;

0 "sulphid"
=>
30 "Yes"
;

0 "silicate"
=>
30 "Yes"
;

0 "graphite"
=>
30 "Yes"
;

0 "oxide"
=>
30 "Yes"
;

0 " inclusion"
=>
30 "Yes"
;

//Question relates to whether or not the component has
//oil holes, greese nipples Question 32

0 "oil"
0 "hole"
=>
32 "Yes"
;

0 "greese"
0 "nip"
=>
32 "Yes"
;

//Question relates to fatigue quesstion 34

0 "fatigue"
=>
34 "Yes"
;

//Question relates to liquid flow Question 37

0 "liquid"
=>
37 "Yes"
;

//Question relates to splines on gears and shafts
Question 45

0 "spline"
=>
45 "Yes"
;

//Question relates to Question 48
//Does the affected area have less
//strength than the parent material

0 " dezincification"
=>
48 "Yes"
;

0 "denick"
=>
48 "Yes"
;

0 "graphitization"
=>
48 "Yes"
;

0 "corrosion"
0 "graphi"
=>
48 "Yes"
;

0 "leach"
=>
48 "Yes"
;

//Question relates to Question 49
//Is there a covering of bacteria,
//fungus, or macro-organisms

0 "bacter"
=>
49 "Yes"
;

0 "fung"
=>
49 "Yes"
;

0 "organism"
=>
49 "Yes"
```

```
;

//Question relates to Question 51
//Has the component been Neutron
//irradiated (Nuclear Reactors,etc)

0 "neutron"
=>
51 "Yes"
;

0 "radiation"
=>
51 "Yes"
;

0 "irradiat"
=>
51 "Yes"
;
0 "nuclear"
=>
51 "Yes"
;

0 "beta"
=>
51 "Yes"
;

0 "gamma"
=>
51 "Yes"
;

//Question relates to Question 52
//What primary component group is your component
//note: shaft does not mean furnaces or excavations

0 "shaft"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "mast"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "pole"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "rail"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "column"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "pillar"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "post"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "stake"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "beam"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "prop"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "truss"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "brace"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "joist"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "rafter"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "girder"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "stay"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
0 "handle"
=>
52 "shafts, masts, poles, struts, rails, threads"
;
//bearings

0 "bearing"
=>
52 "Bearings"
;
0 "coupling"
=>
52 "Bearings"
;

//pipes, tanks, & other fluid holding
0 "pipe"
```

```
=>
52 "pipes, tanks, & other fluid holding "
;
0 "tank"
=>
52 "pipes, tanks, & other fluid holding "
;
0 "hose"
=>
52 "pipes, tanks, & other fluid holding "
;
0 "tube"
=>
52 "pipes, tanks, & other fluid holding "
;
0 "aqueduct"
=>
52 "pipes, tanks, & other fluid holding "
;
0 "contain"
=>
52 "pipes, tanks, & other fluid holding "
;

0 "vessel"
=>
52 "pipes, tanks, & other fluid holding "
;

0 "receptacle"
=>
52 "pipes, tanks, & other fluid holding "
;

0 "bottle"
=>
52 "pipes, tanks, & other fluid holding "
;
0 "dish"
=>
52 "pipes, tanks, & other fluid holding "
;

0 "vat"
=>
52 "pipes, tanks, & other fluid holding "
;

0 "sink"
=>
52 "pipes, tanks, & other fluid holding "
;

//gears

0 "gear"
=>
52 "gears "
;
0 "transmission"
=>
52 "gear"
;

0 "torque"
0 "convert"
=>
52 "gears "
;

0 "mech"
0 "drive"
=>
52 "gears"
;

0 "hobbing"
=>
52 "gears"
;

0 "groov"
=>
52 "gears"
;

0 "bevel"
=>
52 "gears "
;
0 "helical"
=>
52 "gear"
;

0 "differential"
=>
52 "gears "
;

0 "herringbone"
=>
52 "gears"
;

0 "hypoid"
=>
52 "gears"
;

0 "pinion"
=>
52 "gears"
;

0 "sprocket"
=>
52 "gears "
;
0 "spur"
```

```
=>
52 "gear"
;

0 "worm"
=>
52 "gears "
;
0 " cog"
=>
52 "gears "
;

//springs
0 "spring"
=>
52 "spring"
;
0 "helical"
=>
52 "spring"
;
0 "leaf"
=>
52 "spring"
;
0 "spiral"
=>
52 "spring"
;
0 "shock"
0 " absorber"
=>
52 "spring"
;
0 "spring"
=>
52 "spring"
;

//welded components

0 "weld"
=>
52 "welded components"
;

0 " braz"
=>
52 "welded components"
;

0 "solder"
=>
52 "welded components"
;

0 "flux"
=>
52 "welded components"
;

0 "plasma"
=>
52 "welded components"
;
0 " arc"
=>
52 "welded components"
;
0 "electrode"
=>
52 "welded components"
;
0 " TIG "
=>
52 "welded components"
;
0 " MIG "
=>
52 "welded components"
;
0 "electroslag"
=>
52 "welded components"
;
0 " MAG "
=>
52 "welded components"
;
0 "oxyacetylene"
=>
52 "welded components"
;
0 "oxyhgdrogen"
=>
52 "welded components"
;
0 "laser"
=>
52 "welded components"
;
0 "thermit"
=>
52 "welded components"
;
0 "bonding"
=>
52 "welded components"
;
0 " bace metal"
=>
52 "welded components"
;
0 "current"
0 "density"
=>
52 "welded components"
;
0 " hard"
```

```
0 " surfacing"
=>
52 "welded components"
;
0 " HAZ "
=>
52 "welded components"
;
0 " heat"
0 "affect"
0 "zon"
=>
52 "welded components"
;
0 "lead"
0 "angle"
=>
52 "welded components"
;
0 "sealing"
=>
52 "welded components"
;
0 "seaming"
=>
52 "welded components"
;
0 " torch"
=>
52 "welded components"
;
0 " filler"
=>
52 "welded components"
;
0 "flux"
=>
52 "welded components"
;

//Lifting equipment such as wire, cable, chain, or hooks
0 "wire"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "chain"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "cable"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "hook"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "rope"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "strand"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;

0 "winding"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;

//hooks etc
0 "swivels"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "hanger"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "pulley"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 "clevis"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;
0 " link"
=>
52 "Lifting equipment (Wire, Chain, cable or hooks)"
;


//Mechanical Fastenings (Rivets, Nuts & Bolts)
0 " nut"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "bolt"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "rivet"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "Fastener"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "clip"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "pin"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 " ring"
```

```
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "screw"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "spike"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "staple"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "stud"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "washer"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "bracket"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "clamp"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "connector"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "coupling"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "fitting"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "hook"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;

0 "interconnection"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
0 "mechanical"
=>
52 "Mechanical Fastenings (Rivets, Nuts & Bolts)"
;
//XXXX
//XXXX Code developed by Jasper Graham-Jones
XXXX

//XXXX Copyright 1996  Date July/August 1996
XXXX

// Question 53 What is the primary process used in
// manufacture Forging related qustions 53
0 "forge"
=>
53 "Forging"
;
0 "forging"
=>
53 "Forging"
;
0 "upset"
=>
53 "Forging"
;
0 "bulging"
=>
53 "Forging"
;
0 "coining"
=>
53 "Forging"
;
0 "forming"
=>
53 "Forging"
;
0 "hot"
0 "work"
=>
53 "Forging"
;
0 "pressing"
=>
53 "Forging"
;
0 "spreading"
=>
53 "Forging"
;
0 "stamping"
=>
53 "Forging"
;
0 "swaging"
=>
53 "Forging"
;

//Casting related questions 53
0 "Casting"
=>
53 "Casting"
;
0 "molding"
=>
53 "Casting"
;
```

```
//Machining related questions 53
0 "machin"
=>
53 "Machining"
;
0 "drill"
=>
53 "Machining"
;
0 "boring"
=>
53 "Machining"
;
0 "broaching"
=>
53 "Machining"
;
0 "milling"
=>
53 "Machining"
;
0 "coring"
=>
53 "Machining"
;
0 "hodding"
=>
53 "Machining"
;
0 "grooving"
=>
53 "Machining"
;
0 "trepanning"
=>
53 "Machining"
;
0 "planing"
=>
53 "Machining"
;
0 "ream"
=>
53 "Machining"
;
0 "routing"
=>
53 "Machining"
;
0 "scalping"
=>
53 "Machining"
;
0 "shaving"
=>
53 "Machining"
;
0 "chamfer"
=>
53 "Machining"
;
0 "bevel"
=>
53 "Machining"
;
0 "facing"
=>
53 "Machining"
;
0 "cutting"
=>
53 "Machining"
;
0 "tapping"
=>
53 "Machining"
;
0 "turning"
=>
53 "Machining"
;
0 "honing"
=>
53 "Machining"
;
0 "knurling"
=>
53 "Machining"
;
0 "shaping"
=>
53 "Machining"
;
0 "thread rolling"
=>
53 "Machining"
;
0 "trimming"
=>
53 "Machining"
;

//Welding related questions 53

0 "weld"
=>
53 "Welding"
;

0 " braz"
=>
53 "Welding"
;

0 "solder"
=>
53 "Welding"
;

0 "flux"
```

```
=>
53 "Welding"
;

0 "plasma"
=>
53 "Welding"
;
0 " arc"
=>
53 "Welding"
;
0 "electrode"
=>
53 "Welding"
;
0 " TIG "
=>
53 "Welding"
;
0 " MIG "
=>
53 "Welding"
;
0 "electroslag"
=>
53 "Welding"
;
0 " MAG "
=>
53 "Welding"
;
0 "oxyacetylene"
=>
53 "Welding"
;
0 "oxyhgdrogen"
=>
53 "Welding"
;
0 "laser"
=>
53 "Welding"
;
0 "thermit"
=>
53 "Welding"
;
0 "bonding"
=>
53 "Welding"
;
0 " bace metal"
=>
53 "Welding"
;
0 "current"
0 "density"
=>
53 "Welding"
;
0 " hard"
0 " surfacing"
=>
53 "Welding"
;
0 " HAZ "
=>
53 "Welding"
;
0 " heat"
0 "affect"
0 "zon"
=>
53 "Welding"
;
0 "lead"
0 "angle"
=>
53 "Welding"
;
0 "sealing"
=>
53 "Welding"
;
0 "seaming"
=>
53 "Welding"
;
0 " torch"
=>
53 "Welding"
;
0 " filler"
=>
53 "Welding"
;
0 "flux"
=>
53 "Welding"
;

//Grinding related to question 53

0 "grind"
=>
53 "Grinding"
;
0 "abrasive"
=>
53 "Grinding"
;
0 " grit "
=>
53 "Grinding"
;
0 "sanders"
=>
53 "Grinding"
;
```

```
0 "wheel"
0 "dress"
=>
53 "Grinding"
;
//Extrusion, or Drawing

0 "Extrusion"
=>
53 "Extrusion, or Drawing"
;
0 "Drawing"
=>
53 "Extrusion, or Drawing"
;
0 "Extrude"
=>
53 "Extrusion, or Drawing"
;
0 "pressing"
=>
53 "Extrusion, or Drawing"
;
0 "forming"
=>
53 "Extrusion, or Drawing"
;
0 "canning"
=>
53 "Extrusion, or Drawing"
;
0 " cans "
=>
53 "Extrusion, or Drawing"
;
0 "stretch"
=>
53 "Extrusion, or Drawing"
;

//Flame cutting
0 "flame cut"
=>
53 "Flame cutting"
;
0 "fusion cut"
=>
53 "Flame cutting"
;
0 "gas cut"
=>
53 "Flame cutting"
;
0 "oxyacatylene cut"
=>
53 "Flame cutting"
;
0 "oxygen cut"
=>
53 "Flame cutting"
;
0 "oxyacetylene"
=>
53 "Flame cutting"
;
0 "scarfing"
=>
53 "Flame cutting"
;

//Riveted seam
0 "Riveted seam"
=>
53 "Riveted seam"
;
0 "Riveted joint"
=>
53 "Riveted seam"
;
0 "Riveting"
=>
53 "Riveted seam"
;
// question 59 Has spalling or
// delamination of the surface
// occurred spalling and related terms
0 "spall"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "spall"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "flaking"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "galling"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "fretting"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "wear"
=>
59 "Spalling or delamination has occurred on the
surface"
;

//delamination and related terms
0 "delamin"
=>
```

```
59 "Spalling or delamination has occurred on the
surface"
;
0 "peel"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "strip"
=>
59 "Spalling or delamination has occurred on the
surface"
;
0 "laminati"
=>
59 "Spalling or delamination has occurred on the
surface"
;

//Question 60 Has the failure initiated within a thread
run
0 "fail"
0 "thread"
=>
60 "YES"
;
0 "fatigue"
0 "thread"
=>
60 "YES"
;

// Question 62 Has the component been cold worked?
0 "cold"
0 "worked"
=>
62 "YES"
```

Appendix 3 Selection of web pages on failure mechanisms

As part of chapter 14, on the use of the Internet to aid in failure analysis, several web pages were written. The idea of these web pages is to link to the expert system and to act as stand alone failure analysis resources. With future developments an on-line expert system is hoped to be included. The web page selection shown below is just an example of the many pages presently either published or in production. The original location http://www.soton.ac.uk/~pjgj for the pages is presently being moved to http://www.mech.port.ac.uk/StaffP/jgj thus there may be system interruptions and errors in link. The first page is the main navigation pages from which hyper text links are followed and return, called the home or index page. The other pages are examples of the different failure mechanisms. The page layout has also changes due to the conversion from landscape web page to portrait A4 layout.

Engineering Failure Analysis & Expert/Knowledge Based Systems

Engineering Materials Southampton University

Under construction

These web pages details research work in progress in the field of Engineering Failure Analysis and the development of Expert and Knowledge based Systems. Much of the work is based around Case-Based Reasoning, which we see as the most appropriate method for the development of Expert System for failure analysis diagnosis.

We have a number of Published & Non-published papers on our research work. We welcome your comments on our work and the web page. As any group we welcome any joint research and any grant to develop our work. Any help in adding to the information in the web page will also be appreciated.

By Jasper Graham-Jones & Brian G. Mellor

Contents

Introduction to our research work
Published & Non-published papers
Text listing of presentations given *(Corrosion96)*
Fundamental sources of failure
Failure Modes; Links
Images of different failed components
Response form

Introduction

Unexpected and premature failures of metallic structures are daily occurrences in industry. An engineer is expected to diagnose reasons for failure correctly and make subsequent decisions. However, it is likely that the engineer might not be aware of all critical failure routes, due to their complexity, and so is ill equipped to examine systematically complex material problems. This, coupled with the lack of readily available information on the influence of design and manufacture on service performance and reliability, means that the failure modes and remedial solutions can be inadequately diagnosed.

To address this problem a computer based "Failure Analysis Diagnostic Expert System" design tool is being developed which not only interactively identifies the failure modes and the critical factors in the design, processing, and end use which cause failures to originate but also suggests methods to improve the reliability of the failed product by considering how materials, design

details, and processing affect the propensity for premature failure. This novel approach is relevant to industry and educational establishments and it uses a Windows artificial intelligent case-based reasoning approach to generic failure diagnostic problems. Currently, the research is based around the elicitation of failure analysis knowledge and the structuring and planning of this knowledge so the expert system behaves in an intelligent and responsive manner. Many problems have arisen, such as, understanding what factors are required to identify the failure mode and in designing a consistent and economical set of questions that are integrated into an efficient questioning strategy. For the systems behaviour to be intelligent and responsive, additional research into interface design and the understanding of human cognitive models for failure analysis decision making is proposed. Which leads to the development of structured models for engineering failures, used within the expert system . Many factors effect failure by modelling it is possible to decide which factor are critical. In using the expert system, the engineer is able to improve interactively the product design quality at the design stage by considering the influences of different designs/processing options on the failure reliability of the final product, thus designing products with increased reliability, safety, cost efficiency with less waste, so giving better quality assurance.

Failure Modes; Links

The Number of failure modes are extensive. A few which have been included within the expert system have been listed below

For a more detailed account of the different failure modes select from the list below covered within the expert system Southampton University Engineering Materials Consultancy Service.

Failure Modes

- Fatigue
- Corrosion
- Impact failures
- Fretting
- Buckling

Component Failures

- Failures relating to Shafts
- Failures relating to Bearings
- Failures relating to Springs

Manufacturing Failures

- Failures relating to Cold Forming
- Fatigue
- Corrosion
- Impact failures
- Fretting
- Buckling

Other Interesting Links on Engineering Failure

If you have any interesting links on Engineering Failure please email Jasper Graham-Jones

? Help | Top | U of S | Search

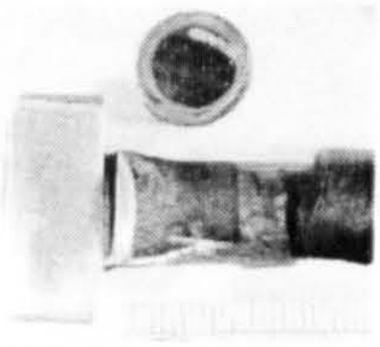
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Within Southampton University
Last modified on Tue March 20.

Images of different failures.

By Jasper Graham-Jones & Brian G. Mellor
Engineering Materials Southampton University
Part of the Engineering Materials Failure Series

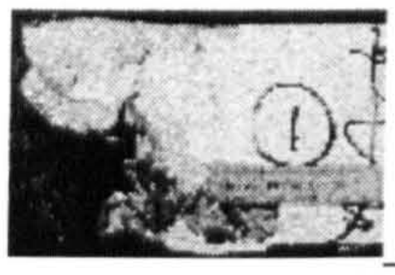
Pick from list:-



Dezincification failure 80k



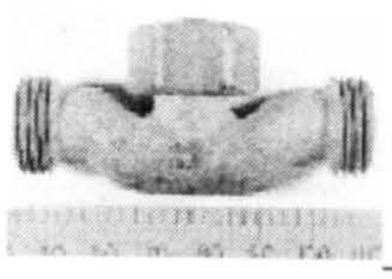
Ladder buckling failure 24k (Buckling)



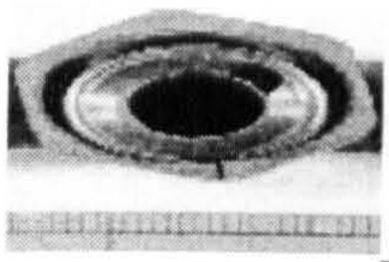
Aluminium alloy mast delamination 36k



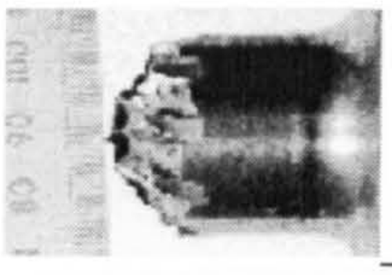
Propellor failed due to fatigue at overlay weld. 16k



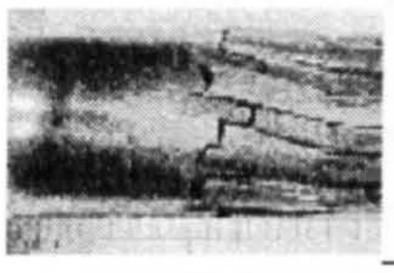
Stress corrosion cracking of a brass nut from an air conditioning plant. 17k



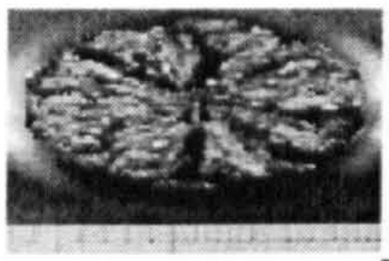
Stress corrosion cracking of brass nut, top view. 13k



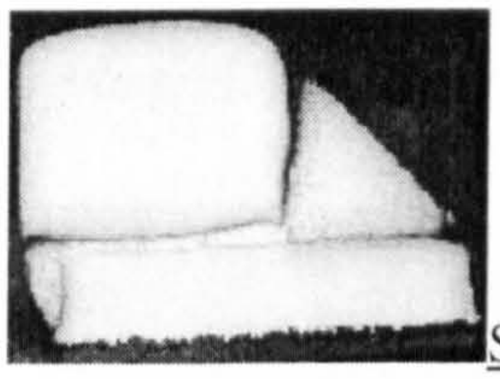
Torsional fatigue failure of a spindled shaft. 19k (Fatigue)



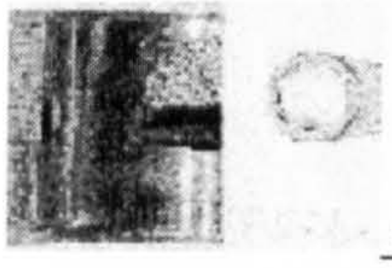
Torsional fatigue failure, side view. 19k



Torsional fatigue failure, top view. 18k



Soldering delamination between electrical contacts. 19k



Connection rod spalling failure. 30k



Ferry stabilizer failure 39k

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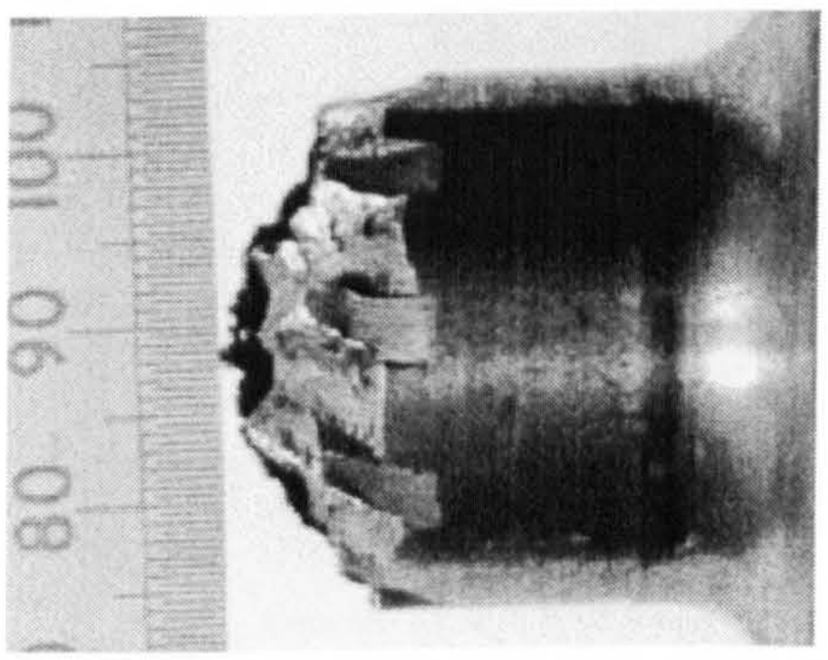
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Fatigue Failures

J. Graham-Jones & B. G. Mellor
Engineering Materials Southampton University

High and Low Cycle Fatigue.

Cyclic or fluctuating load can produce a fatigue failure. If the failure occurs after 10,000 cycles it is termed High Cycle Fatigue". If it is under 10,000 cycles it is termed Low Cycle Fatigue. This is a very simple definition. In real terms, the difference is related to the amount of plastic or elastic strain (deformation) that takes place during each cycle. High plastic strain, fast crack growth and short fatigue lives, i.e. few cycles to failure, are associated to Low Cycle Fatigue. Whereas, strain cycles mainly in the elastic range, lower loads, slow crack growth, and long fatigue lives, i.e. many cycles to failure, is associated with High Cycle Fatigue. Recently Low Cycle Fatigue has been termed "cyclic strain- controlled fatigue. This is due to the use of high cyclic loads in the design of short life produces such as missiles, etc. If a component is under the effects of high cyclic fatigue i.e. mostly elastic strain cycling, and there is an introduction of thermal cycling, as found in ovens, boilers, etc, then the fatigue mode could change to low cycle with its associated short fatigue life. To distinguish between the two failure modes, visual examination of the fracture surface can be used. High cycle, low stress fatigue, shows as a large area of fatigue striations and a small final failure zone. Whereas Low cycle, high stress fatigue shows as a rougher and smaller fatigue zone and a large final failure zone. Sometimes, there is a mix of the two, but failures like this start of with smooth high cycle behaviour, but when the cross sectional area reduces, the stress increase. The increase can produce the rougher and smaller fatigue zone and large final fracture zone. Thus the fracture surface has three zones, high cycle, low cycle, and final failure.



Ref; Collins, J.A.,"Failure of Materials in Mechanical Design", 2rd Ed., Wiley Inter Science, 1993, pp178-413. Metals Handbook, Failure Analysis, 9th Ed., Vol.11, 1986, pp102- 135.

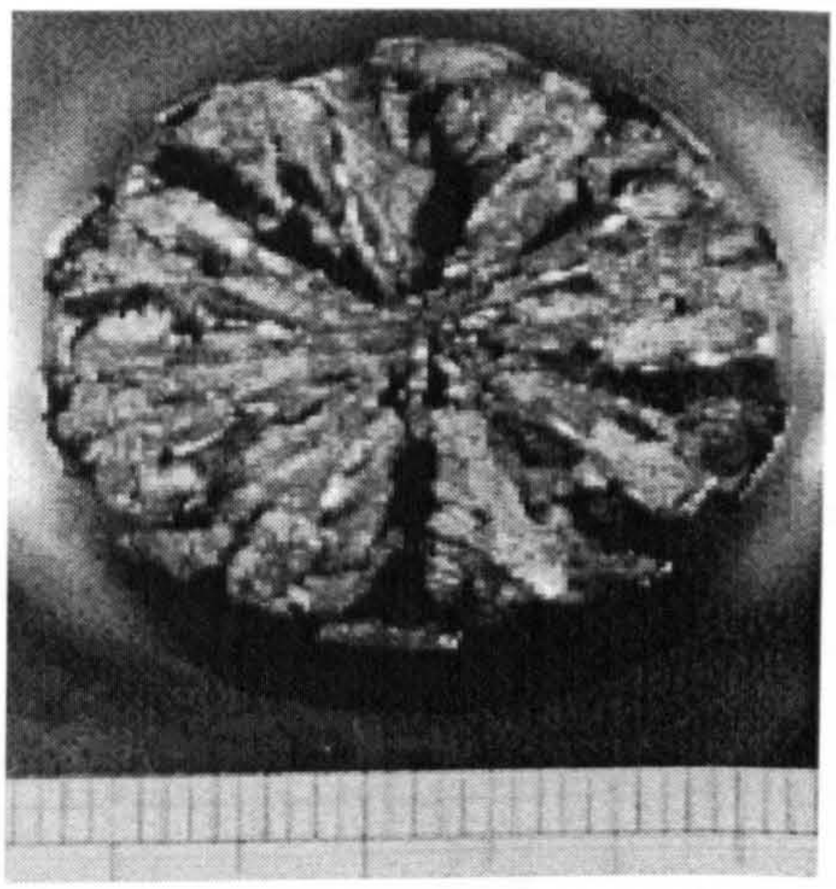
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Torsional Fatigue Failures

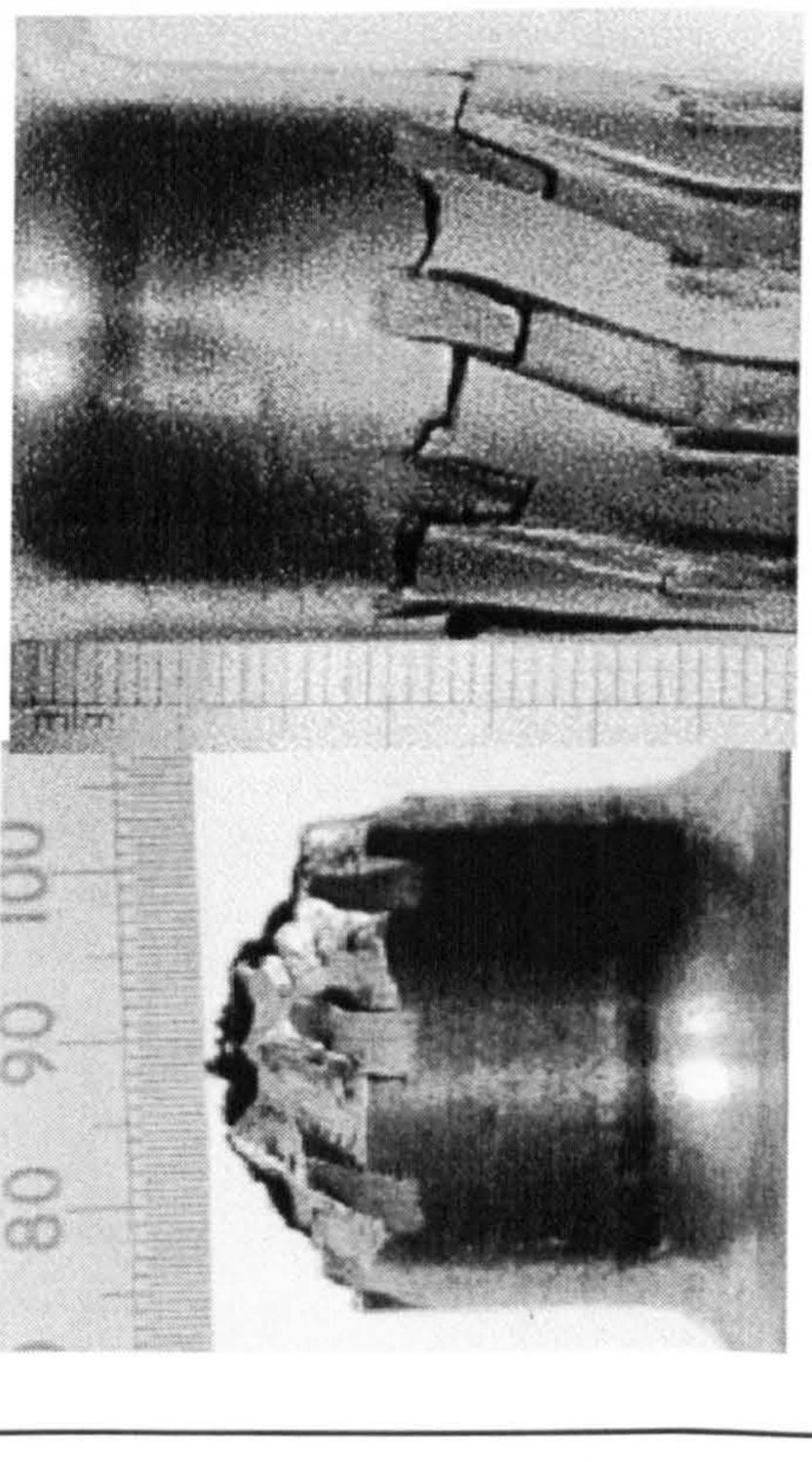
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By J. Graham-Jones & B.G. Mellor



Torsional Fatigue Failure of shafts can be seen by the star-formation on the fracture surface. Typically the initiation starts at keyways, holes, splines and changes in cross section. Multiple initiations from each stress raiser are not uncommon (splines). Cracks are at 45 degrees to the shaft axis.

Torsional Failures are more common in shafts as the shaft is under a greater load than its mating bore. Splines can extend along either a shaft or a bored hole in a shaft. The splines are intended to transmit a torsional load. Each spline may be a stress raiser that could be the source of a fatigue crack, especially if the root radius is small or damaged through poor machining. A typical failure mode could be via torsional fatigue, in which case the fatigue crack propagates at 45° to the shaft/ gear axis to produce a star-shaped pattern on the fracture surface. Failures are more common in shafts as the shaft is under a greater load than its mating bore.



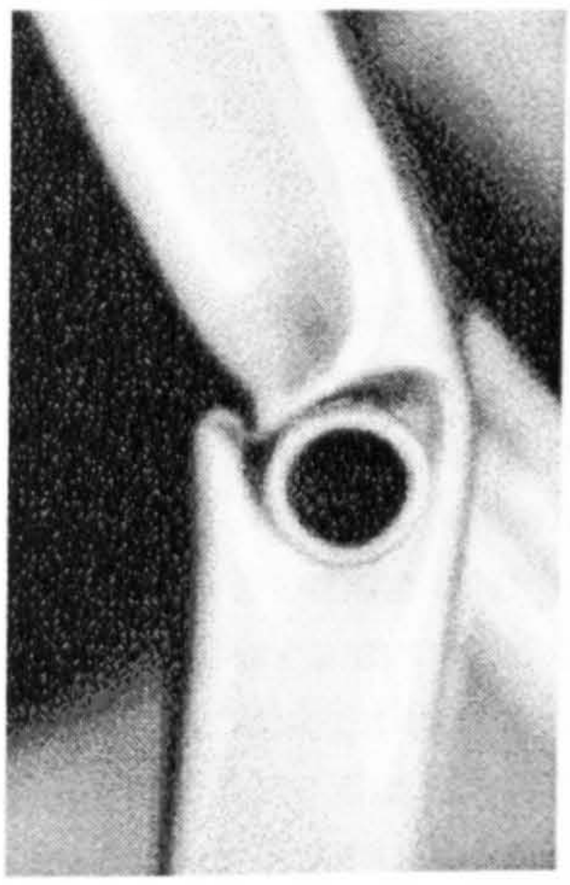
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Buckling failures.

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By J. Graham-Jones & B.G. Mellor



Buckling is a compression related failure that occurs after a critical load produces sudden change in geometry such as a bulge, bend, bow, kink, or other wavy condition within a beam, strut column, plate, bar, or sheet product including thin wall cylinders. The critical load is generally within acceptable designed load ranges for a material, but the geometry change produces an unstable structural configuration, which leads to a sudden collapse. Buckling failures do not depend on the strength of the material but on the structural dimensions, the modulus of elasticity of the material, and the mis-alignment of the load from their neutral axis.

Ref; Collins, J.A.,"Failure of Materials in Mechanical Design", 2rd Ed., Wiley Inter Science, 1993, pp583-608. Metals Handbook, Failure Analysis, 9th Ed., Vol.11, 1986.

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Impact Failures

By Jasper Graham-Jones & Brian G. Mellor
Engineering Materials Southampton University

An impact failure results when a surface is subjected to an especially severe shock load such as that caused by an instantaneous arrest of a (falling) mass; by the shock meeting of two parts (e.g. hammer, nail, dog gear, etc.); or by an explosive impact, in which there can be an exceptionally rapid dynamic build-up of stress and strain loadings. This loading can produce (Impact)fractures and (Impact)deformations to the extent that the design function cannot be performed. Impact Wear, and Impact Fatigue are also found when the loadings are repetitive. When the repetitive loadings induce a micro movement between the two surfaces, due to poisson strains or tangential glancing velocity components; impact fretting can occur. Although, impact is seen as the bringing together of parts, it can also be induced as a shock loading within the component. For example an impact load could be situated at a strong section of a component but induce a shock load to a weaker/smaller section, where the loading could induce a fracture. Thus shock loads do not necessary mean contact with another solid but have the same effect as impact loads. A classical shock load could come from an explosion. An explosion or impact load can lead to spalling and scabbing on the free or opposite surface for the load. This is further discussed in Rinehart (1960, 1951) work.

Ref; Rinehart, J.S.,"Practical countermeasures for the prevention of spallation", Colorado school of mines, Research Foundation Report AF-SWC-TR-60-7 to Air Force Special Weapons Centre, Albuquerque, 1960.

Rinehart, J.S.,"Some Quantitative Data Bearing on the scabbing of metals under explosive Attack", Journal of Applied Physics, vol.22, No.5 (1951): 555-560.

Collins, J.A.,"Failure of Materials in Mechanical Design", 2rd Ed., Wiley Inter Science, 1993.

Metals Handbook, Failure Analysis, 9th Ed., Vol.11, 1986.



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