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REVIEW STUDY ON THE REQUIREMENTS FOR DEEP OCEAN REMOTE HANDLING EQUIPMENT

by

N.C. Flemming and J.S.M. Rusby

November 1983

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REPORT TO EUROPEAN ATOMIC ENERGY COMMUNITY

ISPRA Establishment of the Joint Research Centre

Contract No: 2149-83-07 ED ISP GB

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(Issue 2)

Report compiled by:

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GENERAL SUMMARY

A review study has been made of the needs of potential users for remote handling equipment, or vehicles, in the deep ocean (2000-6000m), and the degree of further technical development required. The study includes an analysis of these needs, of the vehicle types involved and the level and progress in the sub-system technology which will be required. An analysis of the future development and requirement for such vehicles follows and the report concludes with a set of recommended vehicle and sub-system studies which could be considered in the second phase of this project. Annexes contain a list of people visited and a bibliography of those references used in the compilation of this report.

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1. OBJECTIVES OF THE STUDY

(1) To classify potential users for deep ocean vehicles and handling systems, and estimate their technical requirements now, and over the next 10 years.

(2) To summarise the characteristics of existing deep ocean vehicles and handling systems and to forecast technically possible future devices.

(3) To identify technical obstacles to the development of new vehicles and handling systems, and to discuss the level and form of research investment required to achieve a solution.

(4) To recommend ways of promoting the development of particular vehicles and handling systems, and of ensuring that the systems devised do in practice meet the requirements of users.

(5) To recommend research and development priorities in respect of materials, components, and subsystems important to the particular vehicles proposed.

(6) To provide a source of information and references for further development of this project.

2. SUMMARY OF CONCLUSIONS

This section contains the conclusions from section 9.

2.1 Major vehicle projects recommended

Ispra is recommended to investigate in Phase II the feasibility of designing, building and operating in Europe:-

2.1.1 A 6000m manned submersible, capable of remaining submerged for at least 4 days, with provision for shifts of crew and scientific observers, sophisticated navigation and data logging, and provision for extensive experimental equipment, including the use of manipulators and work tools.

2.1.2 A hybrid "piggy-back" submersible system consisting of a large mother submarine capable of diving to 1000-2000m and carrying a smaller deep ocean vehicle capable of descending to 6000m with a useful work payload.

2.1.3 An Untethered Remote Operated Vehicle with a depth capability of 6000m and useful payload, including integrated navigation with 'intelligent' control systems, 24 hours endurance and a high rate of data gathering with large volume storage.

2.1.4 A 6000m Remote Operated Vehicle, lowered in a 'garage', and capable of conducting sorties from the garage using an umbilical connection. Required to carry sophisticated work tools and video equipment.

2.2 Recommendations regarding subsystem development

Ispra is recommended in Phase II to investigate the feasibility of aiding the development of the following subsystems and technologies within Europe:-

2.2.1 New materials, including carbon/graphite/kevlar fibre composites, metal-ceramic composites, etc., should be tested and developed for the construction of large pressure vessels, and other components in manned and unmanned vehicles for deep ocean use.

2.2.2 The use of novel energy sources, particularly the closed cycle Stirling and diesel engine and their associated fuel systems, and certain secondary batteries, should be investigated. Comparative trials, and development and modifications should be carried out to evaluate the potential of each type of power source in realistic working conditions at sea.

2.2.3 Advanced computer and processing techniques, including the development of artificial intelligence, should be applied to the problems of controlling Untethered Remote Operated Vehicles and other systems to minimise the effects of low data rate and delay in signal transmission.

2.2.4 Development should be undertaken in advanced navigation systems for both manned and unmanned vehicles, integrating the optimum performance available from systems employing acoustic beacons, electro-magnetic logs, inertial navigation, etc. Terrain following systems should be investigated for fast near-bottom surveys and the safe operation of manned and unmanned free vehicles.

2.2.5 Improved visualisation and acoustic imaging techniques, including pattern recognition schemes, should be developed for the better control of ROVs and work tools. Stereographic and holographic systems should be investigated.

2.2.6 Further development is needed, and test facilities are required, for umbilical cables capable of combining fibre optics with strain members and other conductors, with a maximum length of 10km.

2.2.7 Test facilities should be developed for investigating the performance of materials, submersible components, subsystems, and assemblies at depths of up to 6000m, both in the laboratory and at sea, with the possibility of leaving materials or systems exposed for long periods.

2.2.8 The French submersible "Argyronête" project should be examined with a view to supporting its development as an underwater test-bed for the sea trials of closed cycle engines and other energy sources, and the testing of other large components and subsystems in realistic operational conditions.

2.3 Procedural recommendations

The discussion throughout this report and the recommendations listed in sections 2 and 9 are based on some general assumptions and judgements concerning the optimum allocation of research and development effort between Ispra and other organisations and users of remote handling systems in the deep ocean. As follows:-

2.3.1 Delegation and decentralisation should be encouraged where possible. If a technique or system can be developed by one laboratory, company, or nation, then it may be wasteful to try and develop it at a European level.

2.3.2 Where a proposed project is too large to be carried out by one laboratory, company, or nation, then there is a strong case that it should be carried out at a European level, provided that the need has been demonstrated. Experienced engineering and administrative leadership will then be crucial to success.

2.3.3 Recommended projects should draw on skills and technology which the survey has shown to be present in European countries. There is every reason to try and synthesise the achievements which now exist in different countries in order to obtain the maximum benefit.

2.3.4 Study, design, and even engineering work should be delegated to specialist laboratories or companies with proven expertise in the field, whenever possible, with Ispra acting as project coordinator. This will capitalise on the value of skills already existing, and provide some exchange of expertise between different organisations participating in a project. It will also minimise possible delays and mistakes which would result from trying to acquire deep ocean engineering experience from scratch.

2.3.5 For the major systems recommended in section 2.1 above it is not reasonable to expect to recover the costs of development, or possibly even the full costs of operation, from certain users. The development of any such major system must be justified on the basis that the use of the system is of value to Europe, and that it is important to have the necessary technological capability within Europe.

2.3.6 In the design, construction, and operating phases of any of the major systems recommended in section 2.1, Ispra should establish advisory groups of experts and potential users of the equipment. Many of the people interviewed during the present study would be prepared to act as consultants in this capacity. The allocation of research time using the systems should be judged by a panel of peer group experts, using the well proven methods of the JOIDES and IPOD drilling projects, and suitable funding arrangements will need to be organised. Such systems should also be made available for commercial charter.

2.3.7 Any major system, if and when developed, will require a professional operating team, both for maintenance of the vehicle, and sea-going operations. This function might best be sub-contracted to a major laboratory or company with the necessary operational experience.

3. DEFINITION OF DEEP OCEAN

3.1 Technical annex to the Contract (No. 2149-83-07 ED ISP GB) requires the study to consider "deep ocean" remote handling equipment. For the purposes of this report the definition of deep ocean will mean in the depth range 2000m to 6000m. The report will nevertheless consider shallower depths in some sections. The reasons are as follows:-

3.2 In the correspondence prior to approval of the Contract there was reference to a submersible capable of working to 6000m. IOS described in its tender its experience and skills relating to work in the depth range 4000-6000m. It is therefore assumed that the objective is to examine systems which are capable, or potentially capable in the future, of operating to these depths. The ocean trench depths extend to 11,000m, but since they are relatively small in area, 3% of the ocean area, the cost of increasing operations to these extreme depths would be excessive in proportion to the benefit. The depth limit of 6000m brings 97% of the ocean floor within reach of the chosen systems, including all the abyssal plains and mid-ocean ridges, as well as the continental slopes and fans.

3.3 Different existing industries and technologies at present operate to different maximum depths. Manned submersible craft have frequently worked below 2000m, and therefore it is reasonable to choose the shallow limit at a depth which is well beyond the conventional 200m depth of the edge of the continental shelf. It is logically reasonable to extrapolate an increased performance from the present manned submersibles which operate in the 2000-3000m zone, to machines which are designed to complete more complex tasks in 6000m. On the other hand, pipe and cable entrenching machinery, and underwater welding, have not yet operated deeper than a few hundred metres. Thus, in order to examine the status quo and find a basis from which to start extrapolation, we have to consider the present function of this equipment in depths shallower than 1000m. The starting point for the study of each system is logically the maximum depth at which it operates at present.

4. RANGE AND LIMITATIONS OF THE STUDY

4.1 The literature has been sampled, and a few hundred references scrutinised. This is a representative sample, but by no means exhaustive.

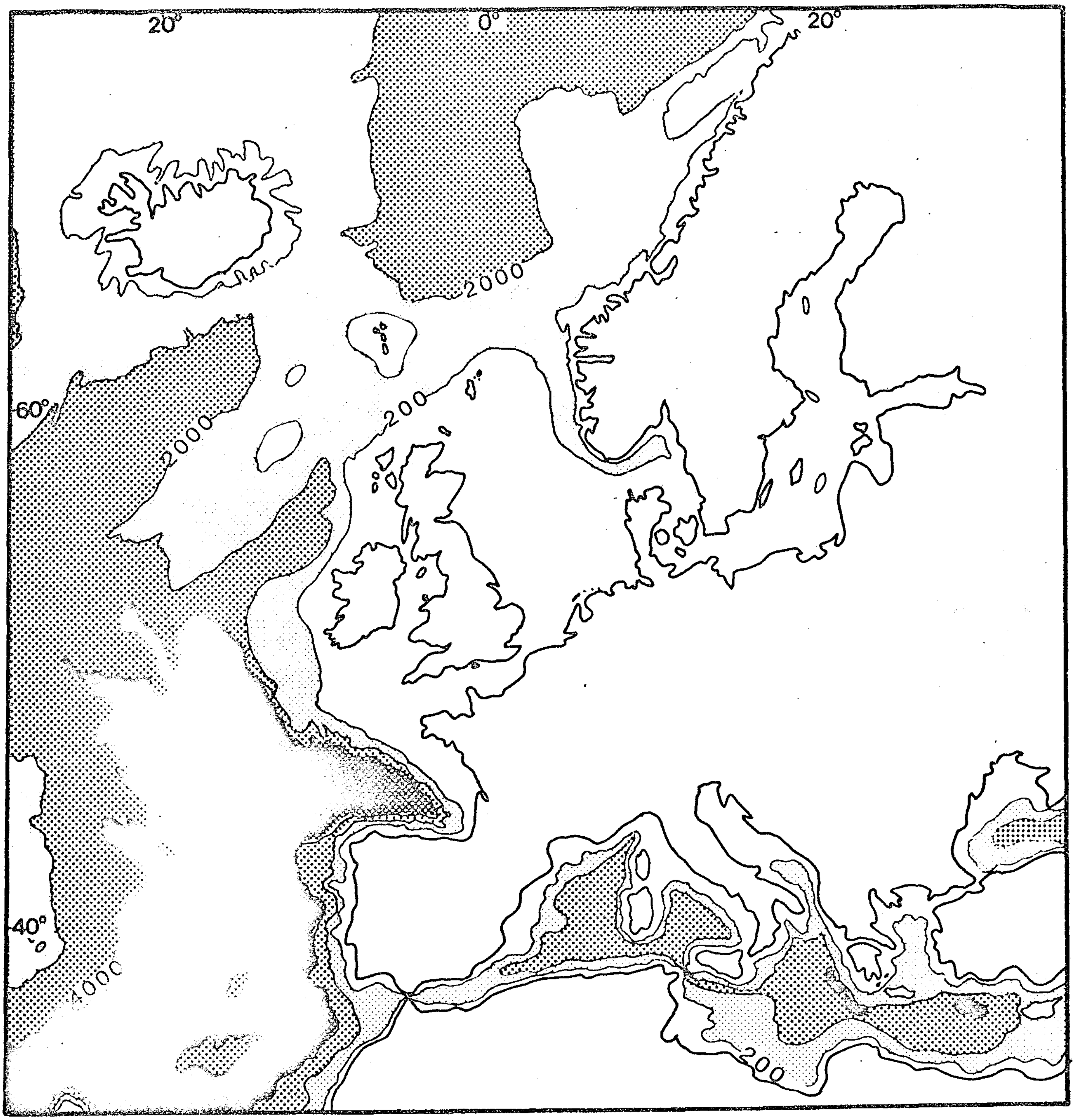
4.2 Interviews have been with typical potential users and manufacturers. The range of companies and individuals interviewed in the time available had to be highly selective (see Appendix 1 for address list of contacts).

4.3 Working from the terminology of the Contract we defined a range of vehicle types (see section 6) which are relevant to the study. Numerous hybrid combinations and variants are possible, such as piggy-backing ROVs on larger submersibles, or deploying remote long-term recording instruments from ROVs, and some of these combinations are discussed. Nevertheless, the range of systems discussed cannot be regarded as exhaustive.

4.4 We have taken examples of existing technology from all over the world, but visits and interviews have been restricted to Europe. Countries visited were France, Italy, Germany, Norway, Sweden, and the United Kingdom.

4.5 Technical analyses have been based on documentary and verbal evidence available, plus the existing skills and knowledge of IOS personnel. No experimental or engineering work or detailed design or costing has been undertaken at any stage.

4.6 Since the area of deep ocean in the European region is rather limited (see Figure 1), we have assumed that European companies, reasearch groups, and military organisations have interests which may extend at times to any part of the world ocean.



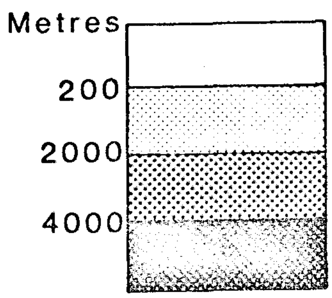


FIGURE 1. Water depths around Europe

5. POTENTIAL USERS OF DEEP OCEAN REMOTE HANDLING EQUIPMENT

For each user section the report will review very briefly the maximum depth of activity of the industry or research now; the depth trend with an approximate prediction of future maximum depth during the next decade; the probability that the activity will require intervention in the deep ocean using remote handling systems; the financial scale of the activity, with some indication of the financial, strategic, or other incentives or motives which might dictate the use of expensive deep ocean intervention systems.

The term "intervention" will be used to mean the use of deep ocean remote handling equipment, whether manned or unmanned. The term will be used in the broadest sense to include the use of all the systems defined in the Contract Phase I. The definitions of the various types of vehicle and machine are given in section 6.

The potential classes of users for deep ocean intervention systems were initially identified as follows. The numbers in brackets refer to the numbers used to list the indexed references in the bibliography. The same numbers are given at the end of each section heading.

(1) Offshore oil and gas industry - exploration and production
(2) Pipelaying
(3) Cablelaying
(4) Manganese nodule mining
(5) Extraction of mineral muds and surface deposits
(6) Commercial fisheries
(7) Repair and maintenance of structures, pipelines, etc.
(8) Inspection and non-destructive testing
(9) Salvage of ships and cargo
(10) Salvage of crashed aircraft
(11) Deployment and recovery of instruments
(12) Radioactive waste disposal

(13) Torpedo recovery
(14) Mine sweeping and removal
(15) Submarine rescue
(16) Biological research
(17) Geophysical and geological research
(18) Physical oceanography
(19) Chemical oceanography

5.1 Offshore oil and gas industry - exploration and production (1)

Oil companies have different views and strategies: some are determined to eliminate the use of divers from their operations as far as possible, and also wish to minimise the use of manned submersibles (BP); others seem content to develop manned systems because of their versatility. Some oil companies have large offshore resources in water depths shallower than 500m, and have little motive to look any deeper; others have limited shallower reserves, and are strongly motivated to search in deep water. The same dichotomy applies to nation states. Thus there is little hope of arriving at a concensus of the needs of oil companies working offshore. However, it is possible to identify general trends, to note the deepest occurrence of any given type of process, installation, or structure in each year, and to make a roughly balanced assessment of future needs.

The stages of developing an oil field which may need manned or ROV type of intervention can be simply outlined as follows:-

Stages of work and intervention:

Geophysical prospecting - minimal
Exploration drilling - possible intervention required
Production drilling and completion - probable intervention required
Production & Workover - intervention required occasionally for maintenance and inspection

We will ignore the geophysical prospecting phase, since there is seldom involvement of mechanical intervention during conventional prospecting, and if sea bed methods were ever introduced, which is unlikely, they would tend to utilise techniques similar to thos described in the Geology-Geophysics user section below.

Exploration drilling

Per Rosengren (NDP - Norwegian Petroleum Directorate) stated that drilling companies operating in the Norwegian sector now conducted drilling without having diving systems on board, and relied on systems which operated without intervention, or on ROVs. BP also stated in UK that they tried to conduct all work without divers and without manned vehicles subsea if possible. Again emphasis was on ROVs and the future use of systems with artificial intelligence. All production of oil and gas in the North Sea is shallower than 300m at present, and in the Norwegian sector there are few plans by oil companies to produce from deeper than 500m before the year 2000. Nevertheless, there is very deep water off the north west coast of Norway, down to 3000m and one potential oil field, Askeladden, has been investigated for BP and Statoil by John Brown Subsea with a view to assessing production potential from 1000m, and a speculative assessment of production from 3000m water depth.

The Norwegian government is in the exceptional position of having more than sufficient oil for all foreseeable future circumstances, and therefore is less concerned to exploit marginal deep water fields than some countries. Even so, Mr. Rosengren did say that since it takes 10 years or more to progress from the decision to explore a field to the date of first production, it was therefore the responsibility of NPD to start planning now for the year 2000 and after.

The deepest exploration drilling off north west Europe has been in the Porcupine Sea Bight and the West Shetlands areas with wells in the depth range 300-500m. Two other recent deep exploration wells are 842m in the Aquila field in the south Adriatic, and 1730m in the Gulf of Lions (Ocean Industry, August 1983). The deepest commercial exploration drilling ever carried out was in August 1983, when Shell Offshore Inc. spudded a well in 2092m of water, 160km southeast of Cape May, New Jersey, USA. This is the first well of a 3-well programme with the deepest in 2307m of water (Ocean Industry, August 1983). The marine riser pipe weighs 1700 tonnes, but is clad in buoyant material supporting 98% of the weight in water. Dynamic positioning of the drillship is by reference to acoustic sea floor beacons. The system is designed to operate without any direct intervention from submersibles etc., but an ROV with TV display on the surface is an integral piece of equipment. Cost of drilling one well in this programme is approximately $50 million (Ocean Industry, October 1982, p41; see also Frisbie, 1983).

The increase in maximum depth of exploration wells has been from 706m in 1975 to 2307m in 1983/84 (Ocean Industry, October 1982). On the conservative estimate of 200m/year the increase over the next decade will be of the order of 2000m, making a maximum depth of 4000m. This is not unreasonable, since technological advances to solve depth-related problems are likely to bring increments of depth capability which are progressively larger. The difference between 50m and 100m is significant; the difference between 2000m and 2050m is not.

Thus it seems highly probable that the technological competence will exist within the next ten years to conduct exploration drilling in 4000m depth, and, on present trend there will be companies willing to bear the cost and risks of such drilling. The depth of 4000m is compatible with the deepest sediment fans of the continental slope, and these are a possible source of hydrocarbons (McKelvey and Wang, 1969). Thus support services and the capability for intervention in the event of loss of equipment or emergencies should be developed progressively to meet this depth requirement.

The actual progress of the depth of exploration offshore will depend critically on the world price of oil, and hence the economics of exploiting marginal fields. Since it is impossible to predict whether the world energy and oil supply will become one of glut and low prices, or shortage and high prices, the only reasonable assumption is that past trends through the last decade will continue more or less consistently over the next decade. Since the last decade has itself seen many economic excursions, this is a fair comparison. In terms of drilling activity, the number of wells drilled between 1970 and 1982 increased from 1370 globally (excluding communist bloc) to 3095 per year. The increase was continuous in every year except 1971 and 1979 (Ocean Industry, October 1982). Vehicles most probably needed during exploration drilling are ROVs, equipped with TV; back-up systems in event of emergency would probably be heavier ROVs with the capacity to work with tools, or pick up lost or damaged gear. The use of manned submersibles is just possible, but would probably only be needed in the case of extreme emergency.

Some measure of the range of work which can now be carried out by an ROV to depths of the order of 2000m are shown in Tables 1 and 2, reproduced from Frisbie, 1983.

Production drilling and completion

Production drilling and completion of the well requires more permanent installations, larger bottom modules or manifolds, more complex installations on the sea floor, equipment to prevent blow-out of oil or gas under pressure, and finally connection of the producing well to a pipeline, either along the sea bed, or vertically to a floating tanker. It is the final engineering stage of completing the well and connecting it to the production system which is depth-limiting.

These operations have in the past required more or less regular intervention by divers or manned vehicles. By definition, all work in the present survey is beyond diver depth. Oil companies are re-designing drilling and production seabed equipment so that interfaces, joints, matings, etc., can be made automatically without welding, and without manned intervention. All informants (BP, Shell, John Brown Subsea, Rosengren) confirmed this point. Nevertheless, the stages of drilling and installing subsea production well-heads, christmas-trees, and gathering modules, is the most complex phase of the engineering operations in the development of a field, and it is during this phase that unpredictable intervention is most likely to be needed. Although the great majority of steps can be designed to be automatic, there will often be the need for visual inspection by ROV, and occasional corrective action or heavy work underwater.

The following represent the primary and contingency work tasks required for the DUAL HYDRA 2500 system. The vehicle capability and tooling is considered as a unit.

(a) Standard Support Operations

Rig Operation	Task
Station & Probe	Place beacons, inspect bottom and measure slope, clear debris. Watch returns while drilling the pilot hole. Look for gas.
Place temporary guide	Inspect, clear debris and visually base and drill out guide placement and orientation of temporary guide base, measure verticality. Watch drilling. Guide any re-entry of bit/hole opener.
Run 30"	Visually guide re-entry of 30". Watch run and land. Check for proper elevation. Watch for cement returns. Visually guide remedial cementing if necessary.
Guide Base Orientation	Establish guide base orientation.
Drill 12 1/4"	Visually guide re-entry, watch drilling.
Open to 26"	Visually guide re-entry, watch drilling.
Run and cement 20"	Inspect, clear debris and guide re-entry, watch running and landing. Watch for cement returns.
Run Riser & Land BOP	Inspect, clear debris and visually guide re-entry, watch landing. Check H-4 indicator rod. Establish BOP orientation.
Test BOP	Inspect stack and riser.
Drill and log test	When abandonment is required inspect stack and riser. Keep bottom free of debris.
Disconnect lower stack	Inspect well.
Pull riser	-
Retrieve wellhead	Visually guide re-entry of cutting/retrieval tools. Watch recover. Inspect bottom and recover debris. Recover beacons.

TABLE 1 : SCOPE OF WORK CARRIED OUT BY DUAL HYDRA 2500 ROV IN 2000m (From Frisbie, 1983)

Vessel: Discoverer Seven Seas Job Description: Rig Support

Location: East Coast USA Client: Shell

Date	Dive No	Depth (fsw)	Duration	Objective
7/30/83	83/001	200	30 mins	Test dive to 200 fsw.
7/31/83	83/002	6448	8 hrs. 17 mins	Deploy Honeywell 906 beacon, observe drill bit tag bottom take bottom sample.
801/83	83/003	4300	2 hrs. 22 mins	Observe running of 48" casing and observe unlatching of running tool.
8/02/83	83/004	4100	2 hrs. 12 mins	Observe running of 48" casing and mud-mats.
8/03/83	83/005	4300	3 hrs. 58 mins	Test dive.
8/04/83	83/006	4000	3 hrs. 36 mins	Test dive.
8/06/83	83/007	6448	4 hrs. 30 mins	Observe and help guide stabbing of drill bit into Perm. Guidebase.
8/09/83	83/008	6448	1 hr. 07 mins	Observe stabbing of drill string for logging operations.
8/10/83	83/009	6448	5 hrs. 01 mins	Stab 26" drill bit.
8/13/83	83/010	6448	4 hrs. 59 mins	Stab 26" drill bit.
8/14/83	83/011	6448	4 hrs. 44 mins	Wellhead inspection.
8/15/83	83/012	6448	8 hrs. 21 mins	Stabbing of 20" casing.
8/19/83	83/013	6448	9 hrs.	Bottom search for lost anode package.
8/23/83	83/014	4700	4 hrs. 30 mins	Test dive to 4700' to put shims on broken strand.
8/26/83	83/015	700	4 hrs. 30 mins	Stack inspection to 700' to check out acoustic beacon arms while stack is being lowered to bottom.
8/28/83	83/016	700	2 hrs. 30 mins	Stack inspection to 700' to check out acoustic beacon arms while stack is being lowered to bottom.
8/31/83	83/017	6448	17 hrs. 10 mins	Riser inspection and standby to land stack.
9/01/83	83/017	6448	10 hrs. 15 mins	Continuation of dive 017 8/31/83.
9/01/83	83/018	6448	8 hrs. 15 mins	Landing BOP Stack.

TABLE 2 : EXTRACT FROM DUAL HYDRA DIVING LOG WHEN CARRYING OUT OPERATIONS IN 2000m OF WATER (From Frisbie, 1983)

The deepest production wells at present proposed include an Exxon subsea completion gas well off the Mississippi Canyon in 460m of water (Ocean Industry, July 1983); a number of wells in various parts of the world are producing oil or gas from 300-350m. Most of these are associated with conventional or nearly conventional platforms, whether rigid or compliant or with production on temporary floating barges. A compliant guyed tower operating in 310m was installed near the Mississippi Canyon in June 1983. Total Oil in conjunction with the Institut Francais du Petrole are developing experimental production systems which are fully floating, with flexible risers, for production to depths of 3000m of water (The Oilman, September 1983). The group are developing automatic pipe repairing equipment for beyond diving depths.

The use of subsea completion systems is envisaged as the method which will be used in the deepest waters, where platforms may not be practicable. A review of subsea production technology (1981 Subsea Production Annual Review) showed 244 subsea production wells worldwide at that date. Only 22 of these were deeper than 150m. A review of developments over 12 months to July 1983 (Ocean Industry, July 1983, p. 47) shows that 57 wells were completed subsea during that period, with the deepest at 270m off Brazil. Fifty three of the subsea completions were achieved with the aid of divers, and only 4 used diverless installation systems. One system is listed as on order for Chevron, Spain, for a depth of 770m in the Montanazo Field, in the Mediterranean (Ocean Industry, July 1983, p. 51). A forecasting review (Ocean Industry, October 1982, p. 78) suggests a maximum depth of subsea production by 1990 of 1000m, and 1200m by 1995. These are the most probable estimates, and the highest estimates for the same dates would be 1200m and 1800m respectively. Saipem confirmed that they at present have contracts providing engineering services and submersible operations to assist production drilling at a depth of 615m, and expect to work to 1000m in the next few years.

At the present date use of subsea completions must be regarded as experimental or marginal in relation to production on surface platforms, even though the technique has been available for 20 years. The Magnus Field in the North Sea employs 7 remote subsea wells connected to a jacket platform in 186m of water. The use of floating platforms, tension-leg platforms, and compliant tower platforms, amongst other systems, has tended to postpone the adoption of true subsea production systems on the large scale. Whatever the future balance between platforms and subsea completions, the cost of platforms is bound to increase with depth, whilst subsea production modules will become relatively more economic. The trend in maximum depth of production will necessarily lag behind that of exploration, and thus a maximum depth of production of 1200-1800m somewhere in the world by 1995 is reasonable in relation to the estimate above of a maximum depth of exploration drilling of 4000m by 1993.

Reliability of the installed production system is critical, and the engineering of this is designed to avoid subsequent intervention (BP, John Brown Subsea). In this context it is noteworthy that one of the world's first subsea christmas trees was recovered from the Santa Barbara Channel in 1983 after 20 years of continuous operation (Ocean Industry, July 1983, p53).

Manned submersibles, ROVs, one-man vehicles, and robotic devices are all used routinely in the final stages of production drilling and completion of wells, whether the completion is subsea, or on a surface platform. Oceaneering Inc. have graded some of the work in terms of "increasing task difficulty" on a scale of 1-10, as follows:-

1	=	Observation
2	=	Simple recovery
3	=	Line cutting, removing debris
4	=	Structural cleaning for visual inspection
5	=	Connecting hydraulic lines and replacing guidelines
6	=	Use of power tools, valve operation, non-destructive testing
7	=	Simple module replacement
8	=	Alignment tasks, flange make-up, replace valve stab overshot
9	=	Sophisticated disassembly and reassembly
10	=	Precision tasks, drill and tap, structural welding

Oceaneering estimate (Subsea Production Annual Review 1981, p136) that multi-person manned submersibles can accomplish tasks up to complexity level 4; but that one-man systems and ROVs can work to complexity level 10. This is presumably because the size and mass of the larger vehicles makes it unsafe to bring them really close to complicated pieces of machinery, and prevents them applying finely judged forces.

In the context of tasks required it should be noted that BP, Shell, John Brown Subsea, and the Norwegian Petroleum Directorate confirmed that welding, below a depth of a few hundred metres, was not practicable, and would be replaced by mechanically or hydraulically made joints. This view was not shared by GKSS Geestacht.

Summary

The oil industry is the largest offshore industry employing intervention systems. We have described the probable future extension into deeper water in some detail, since past events show that this industry is the biggest customer for high technology deep water systems. There will be a major requirement for intervention to 1200-1800m by 1995, and a secondary requirement to 4000m. There will be no likelihood of oil exploration extending to depths in excess of 4000m.

5.2 Pipelaying (2)

Willat and Cameron (1983) describe a powered tracked vehicle for ploughing a bottom trench and burying a pipe or cable. A list of 19 seabed vehicles is included in this paper. Most of the systems are designed to operate on the continental shelf to depths of 200-300m.

Pipelaying will normally be conducted to depths very similar to that of oil production. The exception is where a deep channel has to be crossed, as from Tunisia to Italy, or from the British Shelf to Norway, where the pipe may at some point extend deeper than the point of production. It is unlikely that pipelaying or pipe maintenance and inspection will have to be carried out significantly deeper than the depth of production, and so the 1995 prediction may be taken as similar to that for oil production at 1200-1800m.

Heavy sea bed machinery is needed to entrench small diameter pipes on the Shelf, to protect them from damage. Pipes larger than about 20" in diameter do not need entrenching on the Shelf (John Brown Subsea; Shell); and no pipelines will need entrenching in deeper water, where they are safe from bottom trawls and anchors. Thus there is no foreseeable need for heavy pipe entrenching and embedding equipment deeper than 200-300m.

5.3 Cablelaying (3)

Submarine cable laying continues to be a major industry, and advanced cable design, repeaters, and the use of fibre-optics, ensure that cables will continue to compete with satellite communication links. Cable entrenching and inspection and repair on the Continental Shelf, shallower than 300m, utilise vehicles and embedding machinery. There are no reports of manned submersibles being used for repairs in deeper water. It is inherently simple to drag for a cable normal to the known trend of the cable. The use of an ROV might be an advantage, but might not reduce ship time sufficiently to justify the extra cost. British Telecom have developed and used a tracked jetting vehicle for trenching and burying communications cables. It is called Sea Dog, and operates only to 300m depth. A sophisticated cable grapnel, cutter, and lifting device is described by Scarfe (1983) for use down to 9100m. McBeth (1974) describes the use of Pisces V for the burial of a telecommunications cable in 1824m depth. It is likely that towed sonar vehicles will be used more in the future to provide routeing information.

5.4 Manganese nodule mining (4)

Manganese nodules occur as a surface layer on the ocean floor in depths of 4000-6000m. The most economically extensive fields occur in the Pacific, although small quantities occur in the Tyrrhenian Basin of the Mediterranean. There are six major consortia seeking to develop the technology to exploit the nodules. These are:-

- Ocean Mining Associations (US Steel; Union Minier; Sun Company; SAMIN)
- Kennecott Consortium (Kennecot Copper; RTZ; Consolidated Gold Fields; BP; Noranda Expl. Inc.; Mitsubishi)
- Ocean Management Inc. (INCO; Preussag; Sumitomo; SEDCO)
- Ocean Mineral Co. (Lockheed; Standard Oil of Indiana; Royal Dutch Shell; Bos Kalis Westminster)
- Deep Ocean Mining Associates (38 Japanese companies)
- French Association for the Study and Research of Nodules (4 French companies)

We received written statements from RTZ; and verbal opinions from CNEXO in France, and GKSS in Germany, who have advised the Preussag consortium (Borcherding et al, 1977). CNEXO are at present part way through a five-year programme of developing a sidescan deep towed vehicle known as SAR to study nodule fields. The other informants were of the opinion that research on nodules is almost at a halt. The reasons have been provided in most detail by reports from RTZ, and can be summarised as follows.

The six consortia have invested of the order of \$0.5 billion so far in nodule development, and several alternative dredging systems have been tested in the deep ocean. The report from RTZ (Littman, 1983) assesses nodule deposits in terms of Abundance, Dispersion, Grade, Water depth, Technology required, producing a general assessment of mineability. Land-based reserves of nickel, copper, and cobalt are estimated to be 25-35 years, even assuming a high growth rate in demand. Thus, to be worth mining, sea bed nodules must be recoverable at a lower cost than land reserves. In order for a nodule mining site to be attractive, the deposit area must be of about 50,000 sq km. That is an area 25% larger than Holland.

Most consortia base the collection method on a vehicle or dredge head which is propelled or dragged along the sea bed; which lifts and separates the nodules from the mud, and pumps them up to a surface ship. Dr. G.G. Santi described an alternative system using a submersible to gather the nodules to a central caisson or submersible barge lying on the ocean bed, which was then lifted to the surface ship. Littman (1983) concludes that the world market does not put an immediate demand on the development of subsea manganese nodules, whilst the uncertain state of the law of the sea acts as a strong disincentive.

Smale-Adams (1983 also of RTZ, estimates that an overall investment of the order of \$1.5 billion would be needed to develop a subsea manganese mining operation. Assuming the average unit cost of producing nickel as 100 units, production from different land sources at present varies from 91 units to 126 units. These are simply break-even production costs, excluding capital recovery charges, taxes, etc. On this index it is estimated that a subsea mining operation would cost 150-200 units, but including capital costs winch these are so high. Although the comparisons are obviously difficult to achieve, Smale Adams concludes that with present and foreseeable technology the cost of producing nickel from the deep ocean is approximately twice that of production from land.

Summary

Manganese nodule mining is being held in abeyance by most consortia, in view of the high costs. Some research is continuing at a low level. If mining were to go ahead, even on a prototype basis, or trial production, investment of the order of $200 million would be needed. The working depth would probably be in the range 4000-6000m. ROVs or deep-towed systems might be needed for inspection work and survey of the nodule fields. In the event of any damage or loss to the dredging system there would almost certainly be an immediate requirement for manned vehicle intervention to facilitate repair or salvage.

5.5 Extraction of mineral muds and surface deposits (5)

Hot brine muds containing mineral salts of nickel, silver, titanium and copper have been found at depth of the order of 2200m (Fanger and Pepelnik, 1979) in the Red Sea. The Preussag mining company of Germany has invested large sums of money in trial dredging operations, with the cooperation of the governments of Saudi Arabia and Sudan. Dr. Pepelnik (GKSS) informed us of the instrumentation used to assess the ore quality during dredging.

The system has been operated without any intervention system within the sense of the present study. The economics of the mineral mud mining seen to be slightly better than for manganese nodule mining, partly because the pay-dirt is already in the form of a liquefied slurry which is relatively easy to pump, because the sea-bed will not be cleaned into bare strips by the dredging operation, and because the states on the adjacent coasts are interested to cooperate and support the project. It does not seem likely that intervention systems will provide a significant contribution to this work.

Sulphide ore bodies have been discovered at several locations on mid-ocean ridges at depths of the order of 2500m. Dr. T.J.G. Francis (IOS) is planning to use the French submersible Cyana to lay out conducting cables to measure the subsurface conductivity characteristics of the ore bodies, and hence to estimate their thickness and volume. There are no commercial plans to mine these ores yet, but research activity on their extent will probably continue for several years, and will involve the use of manned submersibles. The Preussag mining company has recently started operations with an instrumented grab to sample sulphide ore bodies (Subtech '83).

5.6 Commercial Fisheries (6)

There are insufficient fish stocks to support commercial fisheries at the depths relating to this study.

5.7 Repair and maintenance of structures, pipelines, etc. (7)

The oil and gas industry is likely to have permanent installations on the sea bed deeper than 1000m by 1990 (see section 5.1). These installations, consisting of well-heads, manifolds connecting several wells, separators, and possibly pumps, compressors, power sources, control valves, and emergency shut-down equipment, etc., will, so far as possible, have the utmost reliability built into them. The equipment will be designed in a modular manner, and maintenance will, so far as possible, be conducted by remote operated robots, lowered on wires, and running on pre-designed tracks integral with the modules. When major repairs are required, a whole module will be detached and replaced. This is a summary of envisaged plans, based on information from BP, Shell, Saipem and Constructors, John Brown Subsea.

However, it is almost inconceivable that equipment as complex as this could be designed to operate predictably, let alone failure-free, for 20-25 years, the typical life of a field. The additional engineering required to ensure such reliability requires greatly increased initial expense, combined with extreme conservatism, and the use of only the most well-tried and proven components. This militates against advanced technology in the design. It seems inevitable that intervention by ROVs or manned submersibles will at times be necessary. If this is accepted from the beginning, it is possible that modules and manifolds can be designed in a more flexible way, allowing for, or assuming, evolution in technology during the life of a field. For example, British Underwater Technology Group have designed a single-atmosphere chamber which is being installed over a gas well-head in Morecambe Bay for British Gas, and which will permit entry at a later date by maintenance engineers. A similar device was tested some years ago for Mobil by the Lockheed company. Such chambers, permitting work to be carried out in a "shirt-sleeves" environment, could be operated well below diver depth, in the 1000-2000m range. Engineers would be transported to the well-heads by a submersible or bell, which locks onto the working chamber. Less complex tasks, inspection, cleaning, non-destructive testing, etc., could be carried out by ROVs.

Summary

Major oil companies will tend to insist that they are going to "design men out of the system" so far as undersea maintenance, inspection, and repair are concerned. It is thus extremely difficult to quantify the real need for manned vehicles. The demand for ROVs is not disputed. It seems that manned systems usually will be regarded as an emergency "fire service", but nevertheless will be demanded, and in some cases will be built into the system in advance. In view of the costs of lost production from shutting down a well, the demand for adequate systems will ensure the continued development of ROVs.

5.8 Inspection and non-destructive testing (8)

The case for carrying out these tasks at depth is similar to that for repair and maintenance (see 5.7 above). It is particularly important that techniques such as photography, video, scrubbing and cleaning surfaces, inspecting welds, acoustic and magnetic tests, etc., should be improved for use with ROVs. Cleaning of metal rig elements by high pressure water jets from an ROV is described by Prior (1983). Magnetic particle inspection is described by Collins and McLeod (1983). Video inspection systems may be improved for oil field inspection by development of stereo wide-angle presentation (Joel Charles, CERTSM; and Biddles, 1983). Some of these activities require that the ROV can be clamped for steadiness to the structure being tested, and that dextrous manipulators can be operated to carry out the tests. Some advances have been made in this by commercial ROV operators. Nevertheless, the degree of control, the resolution of the video information to the control console, and the feedback of information, place demands on the design at the very limits of present technology. Further development is definitely needed.

5.9 Salvage of ships and cargo (9)

Ships containing previous non-ferrous cargoes such as tin, copper or gold, are routinely salvaged by such contractors as Schmidt-Risdon-Beasely, or Micoperi. The salvage of gold bars from the wreck of HMS Edinburgh at a depth of about 200m by the diving contractor Wharton-Williams has drawn dramatic attention to the possibilities. Most work of this kind is achieved by using explosive to open up the hull, and to guide the movements of a grab lowered from the support ship. It is very unusual to use divers or submersibles in commercial salvage of this kind.

In contrast to professional commercial salvage, treasure salvage by more amateur groups has been carried out very successfully for gold coins in 17th-18th Century wrecks, employing teams of compressed air divers. There is no reason to suppose that all ships of this period sank in shallow water, and so there may be a considerable target of a similar nature in deep water. Attempts at salvage are complicated by antiquities legislation in many countries, and the restrictions of the Law of the Sea, Third Convention.

Since modern wrecks can be located relatively easily using magnetometers and side-scan sonar, the use of ROVs to improve inspection would be logical. The supervision of the salvage process could also be carried out more safely, and probably more cheaply, using an ROV, rather than a manned chamber, especially at depths greater than 1000m.

5.10 Salvage of crashed aircraft (10)

The French Navy recently salvaged a crashed military helicopter from a depth of 2300m using a combination of the Cyana submersible, and lifting gear from a cable laying ship. (Information from GISMER, Toulon). Past deep water operations include the salvage of a US Navy Tomcat carrier-borne fighter aircraft which was lost in a depth of the order of 500m near the Shetland Islands. In that case the US Navy brought a submersible from the USA to conduct the initial search. These operations are relatively rare, but there is a very great incentive to achieve success, especially when a prototype or military aircraft is involved. In 1982 the Scorpi vehicle was used to recover a classified military package from 1384m (Watt, SubSea International). The recent loss of the South Korean Boeing 747 airline in Sea of Okhotsk resulted in the US and Soviet Union both deploying manned submersibles in an endeavour to retrieve the flight recorder.

5.11 Deployment and recovery of instruments (11)

Many research projects (see sections 5.16, 5.17, 5.18, 5.19) require instruments to be installed in precise locations, or in a planned array. Instruments with a long effective life in situ, may be unable to store or record data continuously or battery life may be limited. For all these reasons, ROVs or manned submersibles, could be efficiently used in the initial deployment of instruments in the deep ocean, in maintenance, data recovery, and battery charging of such instruments, and possibly in their recovery. A particular need would be for an ROV or manned submersible to be available to release instrument moorings and autonomous landers which had failed to surface on acoustic command (see section 5.18).

5.12 Radioactive waste disposal (12)

The disposal of high level radioactive waste beneath the sediments of the deep ocean floor is being investigated by international committees including both European and American agencies. The preliminary research consists of fundamental chemistry, geology, and biology, and will be discussed below. Various schemes have been proposed for the actual disposal of cannisters of radioactive waste within the deep ocean sediments. These involve the lowering of cannisters under control into bore holes, or the dropping of cannisters using free fall projectiles. The cannisters, weighing several tons, have to be transported to the dump site, and transferred from the transporting vessel to a permanently stationed dumping vessel. At all stages there is a finite, but very small, chance that a cannister may be dropped at the wrong time, or in the wrong place, or that it will break. Additionally, after cannisters are emplaced beneath the sediments, monitoring may reveal anomalously high concentrations of radio-activity, suggesting that a cannister is leaking. The Lockheed Deep Quest submersible, with a maximum operating depth of 2460m, has been used to check the dump sites of radioactive waste used by US authorities. This is presumably not high level waste. Cannisters have been found dumped en route to the scheduled dump site (Subtech '83, oral statement).

Although the accidents suggested above are of low probability, it would be difficult to demonstrate their total impossibility. In order to demonstrate that all possible circumstances had been anticipated, it would be necessary for any organisation planning to conduct controlled dumping of high level radioactive waste to show that it could deal with such accidents. ROVs and manned submersibles would probably both be needed. Navigation would be of prime importance; the cannister or individual dump site would have to be located; and then either the damaged or broken materials lifted from the sea bed, or the sediment overburden dredged out to permit recovery of the buried cannister. In view of the political sensitivity, no cost would be spared in such a salvage effort.

No decision has been taken regarding the feasibility of dumping high level radioactive waste beneath the seabed. Nevertheless, if such a decision were positive, the capacity for prolonged intervention and work on the deep ocean floor must be a pre-requisite for safe dumping. This would include monitoring the implantation of the waste, the effectiveness of backfilling, the level of radionucleide dispersion and the design of procedures to cope with emergencies. Due to the likely depths of such activities, 5000-6000m, the use of ROVs and manned and unmanned free-swimming vehicles would be important.

5.13 Torpedo recovery (13)

No detailed survey of naval needs has been conducted. The loss of torpedoes in deep water, that is deeper than 100m or so, is not common. However, if one includes other military material, munitions, rocket parts, etc., the requirement may be greater. The Royal Navy has developed its own ROV design for torpedo recovery on ranges off the British Isles, and has recently purchased a Scorpio ROV capable of working at 1000m. The Royal Navy has also chartered commercial diving and salvage vessels to help recover equipment lost at sea during the Falklands campaign. The Royal Norwegian Navy has chartered civilian ROVs for torpedo recovery in

100m. In the event of loss of equipment in deeper water, it is possible that any European navy would wish to charter civilian deep ocean intervention equipment.

5.14 Mine sweeping and removal (14)

The US Navy has tested ROVs for mine destruction, and has recently ordered over 100 ROVs for this purpose. A demolition charge is placed next to the mine, and detonated remotely. Presumably most mines are deployed in water shallower than 100m. Anti-submarine mines, nuclear devices, or mines which are moored and later float to the surface, may be placed in deep water, and these could be detected and destroyed by deep water ROVs, or untethered ROVs. Thus, in principle, experience developed in the civilian sector could be of value to European navies.

5.15 Submarine rescue (15)

The US Navy has developed two Deep Sea Rescue Vehicles (Mystic and Avalon) which were launched in 1970/71. Their operating depth is 1524m. The vehicles are air-transportable, and working trials have been conducted with the US Navy, as well as with the British, French, and Italian Navies in Europe. Trials have also been conducted off Scotland in which commercial diver lock-out submersibles were successfully used to evacuate submariners from a military submarine. The French Navy (GERS) informed us that they only have systems which could dive down to a crashed submarine and attach a breathing air line. They could not evacuate the crew. The British Navy has developed an in-water breathing system which allows submariners to escape individually from submarines to a depth of about 300m, but no deeper.

Kockums Varv in Sweden have constructed and tested a rescue submarine for the Royal Swedish Navy which can be towed submerged to the rescue site, and which then locks on to the crashed submarine, and evacuates the crew. Since the maximum depth of operation is within the Baltic, the depth limit is only 460m. The weight of the vehicle is 50 tons in air, and can carry 20-35 people in an emergency.

The deepest submarine rescue on record is the rescue of the Pisces vehicle which sank in the southern Irish Sea in a depth of 500m in about 1974. Rescue was achieved by using the American CURV ROV, backed up by further Pisces submersibles. The rescue ROVs and submersibles were air-transported to Ireland. The first line was attached by the ROV, and the damaged vehicle was eventually hauled to the surface. The rescue operation took about three days, and was completed within a few hours of exhaustion of the on-board life support. The crew of two survived.

Existing rescue systems seem sufficient to cope with crashed submarines down to depths of 1524m, though in emergency the services of additional civilian submersibles or ROVs might be called upon. The limiting depth at which rescue would be required depends on the collapse depth of the hulls of the military submarines which are in operation. If a future generation of military hunter-killer or missile-launching submarine had a collapse depth deeper than 1524m, there would be no possibility of rescuing the crew if, in the event of accident, it grounded on the sea bed in a depth of 2000m. In the European context it might be preferable to adapt civilian submersibles for rescue, rather than to develop a separate military capability, or to rely upon the USA.

5.16 Biological research (16)

Interviews were conducted with Dr. Martin Angel (IOS); Dr. Myriam Sibuet (COB); Professor Torben Wolf, Denmark; Dr. Hjalmar Thiel and Dr. Olaf Pfannkuche, Hamburg.

The importance of knowledge of the biology of the deep oceans is very great, but it is only studied at a few laboratories in Europe because of the high cost. We interviewed biologists from IOS (Britain), COB (France) and the University of Hamburg (Germany). Benthic ocean biological processes have recently been found to be much more closely connected to ocean surface biology than expected, and to be more complex and dynamic than anticipated. This is relevant to any kind of deep ocean waste disposal, to understanding bottom water circulation, to studies of palaeoclimatic data based on oceanic fossils, and indirectly to climate research.

At present there are no time series of repeated observations at precise and repeatable locations for the deep ocean. Yet recent research shows that the benthic biology is extremely variable both in time and space. The processes can only be understood by precise sampling, strategic experiments, and long time series of accurate data. Key issues are the rate of supply of food from mid-water to the ocean floor; the sequence of events which follows a massive food fall at one point; bottom food chain sequences and predation; and the recirculation of organic materials after feeding. The physiological processes of the benthic layer are an essential part of the total circulation of chemicals and nutrients throughout the ocean. Time and space variability need to be studied on scales of hours to years, and from metres to kilometres.

Photography only gives data on the epifauna and burrowing fauna. To obtain data on the rates of processes and fluxes of particles to the sea bottom, COB have deployed free-fall acoustically controlled sediment traps. The next step would be to moor mid-water traps which open and close over periods of several months, to try and correlate the supply of organic materials from top to bottom of the water column.

It is important to measure the rate of use of organic material by the fauna in situ. This will involve measuring the rates of growth of sea bed species, respiration, physiological processes, and reproduction. These experiments will require the measurement of oxygen consumption and production in situ, which is at present not possible. Work is in progress on the development of suitable oxygen sensors.

It would be extremely valuable to tag mechanically individual specimens and study migrations and navigation methods of species. Observations to date from manned submersibles have revealed only adult specimens. The appearance and abundance of juvenile specimens is still a mystery. Deep sea fauna probably have swimming larvae, and biologists do not know what their range of movement or migration is, vertically or horizontally. These factors would influence the transfer of pollutants upwards into the water column.

The University of Hamburg have used a benthic photographic towed sledge operating at 5000m depth. The sledge was extremely strong and stable, and was used for towing through areas where barrels of nuclear waste had been dumped. The camera held 60m of film, and the repeat time with flash was 2.5 seconds. Dr. Thiel expressed an interest in using a deep submersible (3000m) for observation of benthic species for developing experiments to examine processes and productivity for the measurement of water properties in the benthic layer, and steering cameras and video to observe individual specimens. Dr. Thiel and Dr. Pfannkuche suggested that a sensible timescale would be to plan a biologists' workshop conference on benthic deep ocean processes in 1984, with a view to major sea bed experiments being conducted in the period 1985-89. This could be achieved with European cooperation, involving especially UK, Germany, France, Denmark, Netherlands, and Sweden.

It was suggested that the measurement of seasonal variations in the deep ocean required cruises every few months for several years, and that no single nation could afford to do this. A European programme could achieve this. An essential point is to ensure that each experiment is really thoroughly designed so that the scientific results fully justify the expense.

The following list provides an illustration of the type of tasks which biologists wish to carry out at depths of 2000-6000m :-

- In situ benthic sampling
- In situ benthic respirometer experiments
- Biological sampling on steep topography
- Observing fish inside canyons
- Observing bottom fish in mid-ocean rift valleys
- Study of small scale physical oceanography near rugged topography, and its effect on the biology
- Biology of the canyons of the south west approaches to Europe
- Biology of steep sedimentary slopes
- Predation and vertical migration of bottom fauna
- Visual recording of deep ocean animal behaviour
- Setting up bottom biological monitoring stations
- Establishing a suite of in situ bottom experiments
- Repeatable line-transect sampling
- Building up repeatable time series in the deep ocean
- Study of mosaic pattern variability on the deep ocean floor
- Analysis of benthic faunal communities and shallow cores in order to detect climatic change
- Measurement of benthic sediment column biological oxygen demand
- Multiple bottom probes to identify small scale variability
- Variable bottom sampling rates to identify tidal, diurnal, and seasonal cycles
- Study of fish debris in annoxic ocean basins
- Study of potential nutrients and fertility of deep ocean water masses
- In situ physiological studies
- Relationship between high pressure physiology and anaesthetics
- Study of rates of colonisation of cleared patches
- Study of spreading of nutrients after a food fall
- Study of transport paths of pollutants

Systems used by deep ocean biologists in Europe to date include:-

(a) Bottom landing static systems for extended time-lapse photography "Bathysnap" at IOS, and a similar instrument at COB.

(b) Towed unmanned remote controlled trawls and bottom sledges equipped with cameras and video (IOS, COB and Hamburg)

(c) Manned untethered submersibles (COB, using Cyana). Hans Fricke, Max-Planck Institut, has used extremely cheap submersibles for biological observation down to 200-300m.

Bottom landing static equipment could be much more sophisticated than at present, with arrays of traps, recording systems triggered by specific events, etc. Closed loop video could be used to recognise events and trigger film cameras. Static instruments could record the events after dumping a large food fall, such as a dead shark, recording chemical, bacterial, sedimentary and biological data. The spread of organic materials through the sea bed, in the fauna, and as solutes in a plume in the water could all be monitored over months, or even years.

Remote Operated Vehicle (ROV) with a bottom cage or garage could be used to observe individual animals, set up experiments and monitor and service them.

Towed unmanned systems, already extensively used, and individual laboratories can cope with evolutionary improvements.

Manned submersibles - the biologists agreed that manned submersibles would be increasingly important in deep ocean work, but needed to be equipped with better navigation, better pay load and more sophisticated sampling and experimental equipment than hitherto. A submersible for benthic biology must be able to move up and down through the bottom layer of 500-1000m thickness in order to monitor migration. Experiments using traps, dye-markers, tags, etc., are envisaged. Physiological studies of oxygen consumption and generation and repeated transect lines would be undertaken. A wide angle field of view, preferably 180^0, is very important to biological observers.

There is a closely corresponding group of deep ocean biologists in Europe, and their key representatives have expressed a strong interest in being kept informed of the progress of the present study (Dr. A. Rice; Dr. Hjalmar Thiel). They would be prepared to form an advisory group to identify the performance requirements for benthic biological systems, and to monitor research applications.

5.17 Geophysical and geological research (17)

In this field interviews were conducted with Dr. Abedik and Dr. Needham of COB, and Dr. Francis and Dr. Searle of IOS. Other information was gained during discussions on instrumentation and equipment, particularly at BOM Toulon.

All informants agreed that there were many applications for deep ocean intervention systems, and the following summary list of experiments and topics was identified:-

Stratigraphic research
Canyon and rock wall sampling
Sediment sampling
Hydrothermal vent studies
Resistivity studies
In situ permeability studies
Geotechnical shear wave propagation
Ground truth for GLORIA (IOS long range side-scan sonar)
Radioactive waste disposal trials and monitoring
Studies of deep sea sulphides
Manganese nodule studies
Ocean bottom seismograph arrays
Geodetic surveying between plate boundaries
Bench mark emplacements
Ocean floor gravity measurements
Re-entry of DSDP and IPOD bore holes for instrument implantation

Installation of ocean bottom tilt meters and strain gauges

Real time transmission of seismic data from the ocean floor to the surface

The equipment already used in deep ocean geophysics and geology is advanced, partly because of the technical support received from research institutes and the military, but more recently due to association with oil prospecting interests and the subject's importance in radioactive waste disposal studies. The dependence of deep ocean geophysical research on the different classes of vehicle system will be described.

Bottom landing static systems

These include a variety of autonomous recording seismographs and some geotechnical instruments. Larger projects include ISHTE, a US joint institute experiment to bury a radionucleide heat source and measure the heat flow field in the surrounding sediments. Also the proposed MANOP lander which consists of a central package which transfers manganese nodules and other geochemical samples to automatic analytical equipment and stores the chemical information digitally. IOS has conducted experiments with free-fall penetrators which would bury themselves in the sediments and could transmit subsurface geotechnical and other data acoustically direct to the sea surface.

Cable lowered bottom landers

This approach is not much used in geophysics for instrument deployment. Apart from the importance of coring, which tends to be in a class of its own, the main examples are for heat flow measurement and in certain geotechnical investigations.

Remote operated vehicles (ROV)

The development of non-military ROVs capable of operating below 1000m has just begun, and we have no record of their being used in geophysical research.

Bottom tracked vehicles

Apart from the RUM vehicle used in the early '60s there is no record of bottom tracked vehicles being used in deep ocean geophysics.

Free-swimming ROV (UROV)

The only UROV to date designed for geophysical or geological research is Epaulard designed by CNEXO at Toulon. This is a vehicle which carries a drag chain for altitude control and can follow a telemetered course for photographic surveying on abyssal plains, primarily for manganese nodule research. It is not able to maintain good terrain-following in rugged topography. Grid tracks can be run at a spacing of 200-300m, much closer than is possible with surface towed instruments. Navigation is at present via a surface acoustic link, but a totally automatic on-board position fixing system is under development, using long base-line geometry.

Towed unmanned systems

This is one of the standard geophysical research methods for acoustic imaging, and seismic and magnetic studies. New systems are being developed at the present time in the UK, USA and France which are designed to tow vehicles carrying side-scan sonar and high resolution reflection seismic gear close to the ocean floor. Systems in existence include Deep Tow and Seamarc 1 and 2 in the USA.

Manned submersibles

The submersibles Alvin, Cyana, and the submarine NR-1 have all been used for geological and geophysical research at depths greater than 1000m over the last decade. The submersibles are limited to dives of 8-12 hours duration, and their performance is further affected by low payload and the limited re-cycled buoyancy available. The principal area of operation of manned submersibles at present is in rugged terrain where there are rock exposures and vertical or near-vertical surfaces. These provide an exposure of varied rock types, which can be sampled in a logical way revealing stratigraphy. Since this is such an important application of the manned submersible, adequately powered rock sampling equipment is essential. This is within the state of the art, but some submersibles are excessively limited by power requirements. The French submersible under construction, SM97, will be larger than Alvin and Cyana, and should have more efficient sampling and coring equipment. The NR-1 has endurance of 10 days under water and is nuclear powered.

Towed or suspended manned systems

These have not been used for geophysical or geological research below 1000m.

Summary of future needs

We believe that there will continue to be research-led developments in the field of bottom landing and towed systems and that these will be managed by the research institutes involved. Many of the research topics and experiments listed at the start of this section, however, are best tackled by use of new techniques involving other vehicle types. In this context we believe the deep ocean ROV will be important, also free-swimming manned and unmanned vehicles.

ROVs have the capacity to carry out a variety of inspection and working tasks in the deep ocean and they have the capability to re-occupy a previously studied position. Such abilities would be valuable in IPOD bore-hole re-entry experiments and in monitoring and sampling radioactive waste disposal trials. They could also be used in setting up bench marks for geodetic studies, for rock sampling and stratigraphic research and a range of geotechnical investigations. Their capabilities are likely to overlap those of manned submersibles in some of these areas. Manned submersibles may not have the same work tool capacity but they are fully mobile and would be needed for more extended surveys involving stratigraphic and sediment sampling. They have applications in carrying out resistivity experiments and the emplacement of bench marks and the monitoring of geodetic experiments. The further uses to which manned submersibles can be put will be dependent on the extent to which performance can be improved through the use of new hull materials and energy sources.

Unmanned free-swimming vehicles have a particular application in geophysical and geological research. They offer the possibility of conducting pre-programmed surveys of a given area of ocean floor at relatively high speed and with much more precise track control than could be provided by a towed system. The stability of the system would enable synthetic aperture sonar to be developed with a great improvement in azimuthal resolution. In addition, for geophysical studies, such a vehicle might be fitted with swath mapping sonar, a sub-bottom profiler to give sediment structure, doppler sonar for velocity relative to the sea bed, obstacle avoidance sonar, a magnetometer, and cameras and TV. The exact suite would depend on available energy and data storage. In addition an integrated navigation system would be needed and an intelligent control system to decide on course, speed and height to follow, when to operate cameras, when to avoid obstacles, etc. Such a technique would enable maps to be produced of the morphology of the sea bed, of sedimentary facies and structure on a scale comparable to that on land. Areas of resource potential, such as concentrations of manganese nodules or polymetallic sulphide or bodies, could be mapped in considerable detail.

5.18 Physical oceanography

Physical oceanographers use a limited number of techniques for collecting current, temperature, salinity and density data from the ocean below 1000m. They heavily invest in current meter moorings, in conductivity/temperature/depth (CTD) packages lowered from the surface and in the deployment of neutrally buoyant floats to track ocean currents. They are not prime users of remote, or 'intervention' systems, as defined in section 6. However, in discussions with scientists at IOS it became clear that there were research needs which could be solved by the use of one or more of such systems.

One problem identified was the need to investigate and release those instrument moorings which had failed to return on acoustic command. Each year a quantity of data is lost, and the capital investment, from this cause. Dragging for a vertically deployed system is usually ineffective and can cost many hours of ship time. If a full ocean depth ROV was available as a portable system, or if a long endurance manned submersible was in the area then these failed systems could be retrieved. This would also allow the source of such problems to be diagnosed.

There is interest in the use of the unmanned ROV (UROV) for making surveys of the temperature and conductivity (salinity) structure of fronts It could be pre-programmed to run a series of tracks through a frontal system using the variation in the parameters being measured as part of the input to its 'intelligent' control system. Various additional sensors could also be added. There would be value in doing such surveys at a number of discrete depths. In another type of experiment the vehicle would be programmed to follow the depth of a constant temperature or salinity layer.

Use of such systems would depend completely on the level of operational cost which would have to be borne by the scientific project concerned.

5.19 Chemical oceanography

There has been an increase in research effort in the last 5-10 years on the chemistry of the deep oceans and the geochemistry of the ocean floor. Most work is being done by scientists in the USA, UK, Germany and Switzerland. This effort has largely arisen from the needs of the radioactive waste disposal programmes and the interests of the ocean mining consortia (see sections 5.4, 5.5 and 5.12). For the bulk of this research autonomous 'moonlanding' vehicles (see section 6.1) have carried the instruments and samplers required, and this is proving to be a cost effective method of making very precise measurements and collecting the necessary uncontaminated samples. For geochemical research requirements alone it is difficult for geochemists to argue for more sophisticated vehicles, and in this respect they are in a similar position to the physicists. They do foresee the extension of experiments such as ISHTE and MANOP into other areas, and there is a particular interest at the moment in considering a range of 'bell jar' experiments, of the form the biologists wish to undertake in respirometry, productivity, etc. This would include 'analytical' experiments, like MANOP, over a long period of time in which a central 'processor' is used and material is fed to it from satellite positions.

They believe that an ROV or manned submersible could be valuable in monitoring and servicing such complex and long term stations, so that the experiment itself is not interrupted while data is extracted or batteries are recharged etc. Manipulation with a high level of dexterity would be required. Such a vehicle could also be used to examine hydrothermal areas and also regions of downwelling for CO_2 investigations. It is understood that at the present level of knowledge, if CO_2 studies in the atmosphere became dominant, it would not be possible to describe the science of oceanic 'ventilation' which allows carbonate dissolution to take place in regions of downwelling.

Dr. Wilson of IOS remarked that the Deep Sea Drilling Project (DSDP, now IPOD) and Geosecs were models of the US ability to get groups with different backgrounds to work together in new technology experiments.

6. DESCRIPTION OF EXISTING CLASSES OF VEHICLES AND REMOTE HANDLING SYSTEMS

Several key reference works have been published: Janes Ocean Technology (1979); Busby (1981) Undersea Vehicles Directory; Busby (1976) Manned submersibles; Vadus and Busby (1979). The purpose of the present section of the report is to define the classes of vehicles and remote handling systems discussed in this review, to clarify terminology, and to summarise very briefly the range of vehicles already in existence. It is logical that recommendations for future action should be based on experience with existing intervention systems. Many hybrid and composite or intermediate systems have recently been planned or postulated. The numbers in brackets refer to those used in the bibliography to list the subject references used.

6.1 Bottom landing static systems (20)

This class is exclusively used for scientific research and its development has recently been accelerated by the need for radioactive waste studies. The vehicle is launched in free-fall, descends to the ocean floor, performs a sequence of measurements or experiments, is triggered by acoustic means to drop ballast, and ascends under its own buoyancy. The vehicle is usually tracked on descent and ascent by acoustic means, and detection at the surface may be aided by a radio beacon and light. Such devices have applications relevant to all scientific disciplines interested in the benthic region; biology, geophysics, physics, geochemistry and geotechnology. Systems developed at IOS for use at depths down to 6000m include Bathysnap, a time-lapse photographic device for observing the epifauna and burrowing fauna over periods up to six months. It has recently observed the fall of flocullent material from deceased plankton blooms. Others include remote recording seismographs to receive signals from both natural and artificial seismic sources, and devices for measuring the temperature and current structure in the bottom benthic layer. Similar devices have been used at other major laboratories.

Larger scale projects for radioactive waste research in the USA include ISHTE, HEBBLE and MANOP which are briefly described in section 5.17.

6.2 Cable lowered bottom lander (21)

This class also is generally only used in research. Instruments such as pore-water probes, specialised samplers and corers and geotechnical devices requiring to exert a load on the sea bed, are lowered into position. The cable is then maintained in a slack condition whilst the experiment is performed, and the device is subsequently retrieved. The dynamics of the impact with the bottom and subsequent cable management have proved difficult to control, particularly from research ships without a precise positioning system. The system merges into certain bottom ROV devices, since in the latter case a heavy "garage" or "cage" is lowered to the bottom, and the ROV exits from this on a tether to perform its work. Various highly specialised bottom landing devices have been built for pipeline repairs etc. (British Underwater Pipeline Engineering (Hydra-Lock) Ltd.; and Saipem).

6.3 Remote Operated Vehicle (ROV) (22)

This is a vehicle supplied with control video and power connections through an umbilical cable usually from a surface support vessel. Vehicles range in size from those weighing 50kg - so-called "flying-eyeballs" to those weighing several tonnes (see Table 3). Increased size permits greater power, heavier manipulators, more cameras and experimental equipment, etc. ROVs have in the last five years improved dramatically in performance, and displaced both divers and manned submersibles for many tasks in the offshore oil industry. The advantages are low human risk, long endurance in the water, ability to work below the diving limit at 300-500m, ability to work within structures, and high data rate transmission to the surface for good video resolution. Over 100 ROVs have been built to work shallower than 1000m, and about ten in the depth range 2000-3000m (Busby, 1981). Frisbie (1983) describes a successful oil drilling support operation deeper than 2000m. The Royal Navy vehicle TUMS can be operated both as

Vehicle	Weight in Air (kg)	Operating Depth (metres)	Speed (kts)	Ratio Power Consumption / Weight in Air (kW/tonne)
Curv IIC	3,100	1,800	4	15
Curv III	2,000	3,000	4	20
Deep Drone	700	1,200	3.5	50
Manta 1.5	1,200	1,500	2	8
RCV-150	1,300	2,000	<2.5	75
RCV-225	180	2,000	1.7	30
RUWS	5,500	6,000	1.5	35
Scarab I&II	2,200	1,800	3	65
Scorpi	300	1,000	3.5	N/A
Smitsub-100	700	1,000	-	200
SOP	1,800	1,000	-	36
Dual-Hydra 2500	7,500 (inc. cage)	5,000		6

TABLE 3 Remote Operated Vehicles (ROVs) capable of working at 1000 m or deeper

a towed vehicle, or as an ROV working from a depressor-cum-cage at abyssal plain depth (Peach and Sear, 1983).

Since ROVs on a short tether can be operated effectively in combination with almost any other system, bottom lander, towed fish, manned submersible, their application seems bound to be very wide, both in depth range and task type.

6.4 Bottom tracked mobile vehicle (23)

Busby (1981) reports only one bottom tracked vehicle working in the depth range 1000-2000m, and none deeper. Willat and Cameron (1983) describe 18 vehicles ranging in weight from 1 tonne to 141 tonnes, without giving depth information. The majority of vehicles move on tracks, and are designed to dig trenches and bury pipelines and cables. Since the bulk of this work needs to be done on the continental shelf, shallower than 300m, where cables and pipes are potentially at risk from ships' anchors and fishing trawls, there is little probability that the systems will be developed for much deeper work.

6.5 Untethered, free-swimming, ROVs (UROV) (24)

Busby (1981) lists 4 UROVs operating below 1000m depth (see Table 4). The vehicle on which we have collected the most data is the French Epaulard (Michel and Le Roux, 1981). This has 6000m operating depth, and works without cable control, responding to automatic controls and the use of a depth chain for maintaining distance from the bottom, and transmitting and receiving signals acoustically in communication with surface support. The advantages of a UROV are freedom from the drag of the umbilical, tight turning circle, freedom from vibration or other motions imparted by the cable, steadiness, and a capability to achieve close terrain-following. The disadvantages are limited power and endurance, complexity, need for the utmost reliability, and difficulty of transmitting high data rates of information and control signals.

Vehicle	Maximum Operating Depth (m)	Vehicle Weight in Air (kg)	Speed (knots) (max)	Operating Duration (hrs)	Power	Communications	Computer	Application
AUSS	6,100	907	7	10	20 kWh Lead Acid Batteries	Acoustic link	3 ea 86-12, 16 bit micro-processors with 8086 CPU	Search
EAVE EAST	914	318	2	6	Lead Acid	Acoustic link	6100 CPU, 1K EPROM, 2K ROM	Pipeline inspection
EAVE WEST	671	181	1.8	1	24V Lead Acid Batteries	Fibre Optics; Acoustic	8080 Micro-processor system	Pipeline inspection
EPAULARD	6,000	3,000	2.5	10	48V, 15kWh Lead Acid Batteries	Acoustic link	N/A	Photography Topographic Profiling
ROBOT SUBMARINE	91	66	3	3	2-gel cell 8 amp-hr Batteries	Preprogrammed	280-based CPU 2K ROM, 1616 dynamic RAM Multiplier Unit	Search, Survey
SPURV I & II	3,000 (I)	454	7	6	Silver Zinc Batteries	Acoustic link	N/A	Water Column Measurements
UPSS	457	N/A	5	25	Lead Acid Batteries	Acoustic link	8080 CPU 24K EPROM, 5K RAM 16 ch. A/D, 12 8-bit I/O	Search

TABLE 4 Untethered vehicles

A UROV can work in a confined space, such as a narrow canyon or between the legs of a rig. Thus it would be logical to operate a UROV from another vehicle, either an ROV or a manned submersible, shortening the acoustic path for the controls. The combination of ROV plus UROV is envisaged by Russell et al (1983). See also Shirley (1981) for computer systems in UROVs. Joel Charles (CERTSM) suggested that the low data rate, and hence poor control, associated with a UROV might be overcome by providing computer artificial intelligence in the vehicle, accepting a low rate of data transmission to the surface, and then using a second artificial intelligence device on the surface to reconstruct the motions of the UROV, and to compensate for the time lag in the acoustic transmission.

6.6 Towed unmanned systems (25)

Busby (1981) identifies 10 deep tow systems, with the majority capable of working between 5000-6000m. (This count of course ignores the many hundreds, or even thousands, of shallow water side-scan sonar and other shallow towed devices). At least two further systems have been developed since 1981, and the IOS and French systems are in the development stage. Various combinations of heavy depressor are used with associated instrument vehicles which are either heavy, neutral, or buoyant relative to the depressor. The objective of the towing system is to decouple the instrument fish from the motions of the ship and the bulk of the cable. The towed system may be combined with the option to station the vessel, allowing the depressor or cage to rest on the bottom, and the fish to be controlled under its own propulsion as an ROV.

The advantages of the deep-tow configuration are ample power for acoustic instrumentation, video and cameras, relatively high towing speed, and high data rate for transmission of signals through the towing cable. The disadvantages are that, at a depth of 5000m, the towing cable will have a length of the order of 10km. It is thus difficult to navigate the fish accurately, and impossible to turn on a tight radius. This makes for a wide line spacing in bottom surveys with poor track control.

6.7 Manned submersibles (26)

Busby (1981) lists 68 submersibles operating shallower than 1000m; 5 in the depth range 1000-2000m; 6 between 2000-4000m; and 1 each in the ranges 5000-6000m, and deeper than 6000m. Since 1981 the US Navy Seacliff has been up-rated from 3000m to 6000m, and the French (CNEXO plus Navy) have commenced construction of the SM-97, which will have 6000m capability. Several other manned vehicles have been built in the shallow range (see Table 5).

There are several major divisions within the general classification of manned submersibles. These divisions are somewhat arbitrary, with indistinct borders, but help to clarify the range of types:

True submersible, a vehicle with a crew of 1-4 people; personnel capsule is as small as practicable, and contains a minimum of machinery; the bulk of power storage, propulsion system, controls, and machinery, is installed outside the pressure hull and designed to work at ambient water pressure. Usually operated from a mother vessel, and lifted out of the water between dives. This has been the classic configuration of submersibles since Cousteau's "Soucoupe" of 1959, and has been retained through to the SM-97.

Submarine type, a vehicle in which almost all sub-systems and machinery are installed within the same pressure hull as the personnel. This is the conventional military submarine pattern. This configuration has been used by IKL-Gabler for the small diesel-electric Tours vehicles, and more recently by Bruker Meerestechnik. Dr. Santi (SSOS) has conducted design studies of a range of submarine-type vehicles using a highly streamlined tear-drop hull, which should provide high speed and long endurance. Bruker Meerestechnik have consturcted a diesel-electric submarine with galley, bunks, etc., for oil field work to a depth of 200m. Weight is 46 tonnes, and length 15.5m (Haas and Kern, 1983) (Seahorse 2).

Vehicle	Weight in Air (tonnes)	Operating Depth (metres)	Collapse Depth (metres)	Payload (kg)	Life Support Duration (man/hr)	Total Energy (kWh)	Speed: Cruise (kts)	Speed: Max. (kts)	Total Crew	Launch Date	Hull Material	Power Source	Ratio Total Energy / Weight in Air (kWh/tonne)	Ratio Payload / Weight in Air (kg/tonne)
Alvin	15.4	3,658	7,620	453	216	42.7	1	2	3	1964	Titanium	Lead Acid	2.77	29.41
Mystic & Avalon (DSRV 1 & 2)	24.6	1,524	2,236	N/A	388	156.8	N/A	3.9	2	1970&1971	HY-140 Steel	Silver Zinc	6.37	N/A
Cyana	8.5	3,000	3,900	199	216	47	1	2	3	1970	Vascojet 90 Steel	Lead Acid	5.52	23.4
Deep Quest	47	2,438	3,962	2700	432	230	2	3	4	1967	KSI Grade Maraging Steel	Lead Acid	4.89	57.44
Pisces IV	10.4	2,012	2,743	590	336	46.2	0.5	2	3	1972	HY-100 Steel	Lead Acid	4.45	56.93
Pisces V	10.8	2,012	2,743	278	528	39	1	2	3	1973	HY-100 Steel	Lead Acid	3.6	25.74
Pisces VI	9.8	2,012	2,743	680	250	42	1	2	3	1976	HY-100 Steel	Lead Acid	4.28	69.38
Pisces VII & XI	10.7	2,000	3,048	679	216	46.2	0.5	2	3	1975 VII 1976 XI	HY-100 Steel	Lead Acid	4.31	63.45
Sea Cliff	23	3,048 (6,000 with titanium sphere)	4,572	N/A	111	30	0.5	2.5	3	1968	HY-100 Steel	Lead Acid	1.3	N/A
Sever 2	28	2,000	N/A	400	216	N/A	2.5	4	3	ca. 1969	N/A	N/A	N/A	14.28
Shinkai 2000	25	2,000	3,300	100	240	61.6	1	3	3	1981 (planned)	NS90 Steel	Silver Zinc Oil	2.46	4
Trieste II	N/A	6,096	9,691	N/A	135	N/A	1.5	N/A	3	1969	HY-120 Steel	Silver Zinc	N/A	N/A
Turtle	23	3,048	4,572	N/A	210	30	0.5	2.5	3	1968	HY-100 Steel	Lead Acid	1.3	N/A
Arms I&II	7.1	914	N/A	310	190	30	N/A	3	2	1976,1977 1979	HY-100 Steel	Lead Acid	4.21	44.58
SM-97	18	6,000	N/A	50	-	40	-	-	3	1984	Titanium	Cadmium-Nickel	2.2	-
NR-1	400	1,000	N/A	N/A	Days-weeks	Nuclear	N/A	N/A	5	1970	Steel	Nuclear	-	-

TABLE 5 Submersible Vehicles capable of working deeper than 1000 m

Vehicles weighing less than 20 tons are usually handled from a large surface support ship, which is expensive to operate. Dives typically last 6-8 hours, and the vehicle is lifted out of the water via a stern A-frame after each dive. Batteries are re-charged on deck, experimental equipment prepared for the next dive, and repairs carried out if necessary. This is the typical mode of operation of the submersible. Since many of the subsystems are outside the manned pressure hull, they can only be serviced on deck, or by divers in shallow water. The advantages are a light vehicle, total control of all parameters of the vehicle when it is on deck, and the security provided by a large conventional surface ship. The crew is never exposed to prolonged stress underwater. The principle disadvantages are the cost of the support ship, the cramped crew conditions, the short dive duration, and the fact that subsystems have to withstand pressure and corrosion, as well as the weather limitations of launch and recovery. Also payload is usually severely limited for the deeper diving submersibles of this type.

The autonomous submersible/submarine is designed to operate without a surface ship. By provision of diesel power and an air-breathing snorkel the vehicle motors on the surface to the work-site. It then converts to a non-air-breathing power system, and dives for as long as the power source will permit. The IKL-Gabler Tours vehicles were unique in being very small, and designed on this principle. They were intended for use in deep water close to shore in the coral industry, but were not commercially very successful. The Bruker Meerestechnik Seahorse 2 is designed to exploit fully the potential of the autonomous concept. Assuming a duration of cruise/dive of several days, the crew are provided with space and facilities for sleeping and changing watches. This of course means that, in addition to the work space and facilities, a great deal of extra space has to be provided within the pressure hull. The advantages are presumed to be the complete avoidance of the costs of the support ship. The disadvantage may be that the vehicle is large and cumbersome when it gets to the work site. Additionally, if problems are encountered during the work they must be solved within the vehicle, without the flexibility provided by the time and facilities on the deck of the support ship. CNEXO-COMEX are proposing to resuscitate the Argyronête vehicle as a test vehicle to develop the concept of an autonomous long-range diver lock-out system, and this experiment could be very valuable. In general, since the autonomous submarine/submersible is likely to be large, of the order of 40-300 tons, it is logical that the basic vehicle should be supplemented with either a ROV or a smaller, more manoeuvrable, submersible to enable dexterous tasks to be performed in confined spaces.

Summary

Manned submersibles have declined in use in the last decade, largely due to the high costs of operation, and the competitiveness of ROVs. However, all submersibles up to the present date have suffered from an acute shortage of total installed energy per dive. Whatever the size, a vehicle dependent upon secondary storage batteries has been boxed in with a set of limitations constrained by its endurance, payload and available power for tools and lights. The designer has had to economise and miniaturise in every department, in order to extract maximum performance from minimum power.

Recent technical developments suggest that constraints of limited power and buoyancy may both be removed within a few years, and the performance of manned submersibles could be greatly improved. These trends will be discussed more fully later. (see sections 7.1, 7.2 and 7.8)

6.8 Towed and suspended manned systems

Various one-atmosphere vertically lowered observation bells, bells with articulated arms, bells with thrusters for limited movement, and towed observation bells, have been used over the last two decades. The devices merge by stages into articulated one-atmosphere diving suits, and small one-man submersibles. Most of these devices operate shallower than 500m and very few as deep as 1000m. Variants of these systems will probably remain in use to support offshore oil field operations, but are unlikely to be developed for use deeper than 1000m.

7. ANALYSIS OF THE DEVELOPMENT NEEDS OF VEHICLE SUB-SYSTEMS

In this section the various sub-systems contributing to the different class of vehicle have been defined, and a brief analysis has been made of the present state of development of each one and its relevance to the vehicle types. The degree of further development which may be required is discussed and recommendations made for particular development if this is appropriate.

The sub-systems have been identified under the following section titles, and will be discussed in order in the following pages. The numbers in brackets refer to those used in the bibliography to list the subject references used.

(28) Power storage, supply and conversion
(29) Prime mover and propulsion systems
(30) Umbilical design
(31) Manipulators, robotic tools
(32) Video systems and video transmission
(33) Navigation, position fixing and track recording
(34) Buoyancy control
(35) Pressure vessel construction and testing and hull throughputs
(36) Data telemetry
(37) Human control, sensory data, feedback, piloting, data display
(38) Life support
(39) Emergency and bale-out systems
(40) Surface support, support ships or platforms and handling systems
(41) Land, sea or air transportability
(42) Maintenance problems
(43) Scientific instruments for use on the vehicle
(44) Scientific data recording on the vehicle
(45) Hydraulic, electrical and mechanical components
(46) Use of on-board computing and microprocessors

7.1 Power storage, supply and conversion (28)

In this section we are concerned with power storage, supply and conversion systems which are relevant to vehicles included in sections 22, 24 and 26 (ROVs, and both manned and unmanned free-swimming vehicles) and also to underwater work and repair systems although the latter are not covered by the review in any detail.

The range of power storage and supply systems which have been proposed over the years for underwater use is large. Some predate the use of nuclear power for submarines and others are related to space vehicle power supplies.

When volume and weight are at a premium, and high performance is essential, then technical complexity and high capital and running costs may be tolerated. This is very much the case in military and space activities. However in civilian underwater applications, for commercial and scientific use, we believe that low costs and technical simplicity are more important, even at the expense of performance criteria. In this context, technical simplicity includes fuel handling and safety technology; many of the more exotic fuels would be difficult, if not impossible, to handle in the civilian field without highly trained and costly staff. For this reason we have not considered storage or supply systems requiring either potentially hazardous free reactants such as hydrogen, lithium and sodium, or nuclear and isotopic sources. As a result, the following primary and secondary systems have been excluded: hydrogen-oxygen alkaline and acid fuel cells (the latter also includes a most complex associated power plant), the lithium-seawater fuel cell, the lithium-peroxide fuel cell, the sodium sulphur battery and the lithium and sulphurhexafluoride heat source (used in conjunction with a closed Brayton cycle turbo-compressor), as well as all energy cycles involving nuclear and isotopic sources. All monopropellant-based power sources have also been excluded, on the basis of cost and safety criteria. This review has included the use of gaseous and liquid oxygen because it is believed handling systems for this reactant are well developed and it is inexpensive. Acceptable fuels are diesel and JP-5 (kerosene); acceptable batteries include lead acid, nickel cadmium, nickel iron, silver zinc, and lithium sulphur (where the lithium is held in a sealed 'dry' form) and we have also taken note of the carbon block rechargeable heat source and the advanced flywheel rechargeable kinetic source (superflywheel).

As a result of the above 'exclusions', only the following two primary, or 'non-rechargeable', options have been considered: The first is a thermal source employing oxygen plus JP-5 in either a closed-cycle reciprocating heat engine (diesel or Stirling) or in a catalytic combustor as the heat source for a turbo-compressor operating in a closed Brayton cycle; and the second is the lithium sulphur primary battery. Oxygen plus JP-5 or diesel fuel is an attractive source of underwater energy. Both components are cheap and easy to obtain, and methods of containment have been well developed over the last few years. Oxygen is stored most efficiently in liquid form (LOX)at about

-170^{o}C and suitable cryogenic vessels have been developed which will store it for up to four weeks without refrigeration. The lithium sulphur primary battery, using either iron disulphide or iron sulphide, has reached a fair level of development in the United Kingdom, and is likely to provide an energy density of 100-130 Wh kg^{-1}. However such a thermal battery has to be kept at a temperature of 400 - 500^{o}C and the cost of a renewable energy source of this type could be prohibitive for underwater activities. Present work is concentrated on the development of a secondary or re-chargeable, form of this battery.

The range of 'allowed' rechargeable sources includes the well-used lead acid and nickel cadmium batteries with energy densities of 30 and 25 Wh/kg, and also those employing the silver zinc, nickel iron and lithium sulphur couples, with energy densities of 50, 75 and some 100 - 130 Wh kg respectively. Recent underwater vehicles have used the developed form of the silver zinc battery successfully but the cycle life is markedly inferior to both the lead acid and nickel cadmium batteries. The United States was active in the field of secondary sources in the 1970s but research has now been reduced severely by Government and industry, mainly because the oil crisis failed to materialise and the navy is believed to have little interest in secondary batteries. The nickel iron battery is under active development in France, it would seem to offer the same good cycle life as the nickel cadmium but with the possibility of twice the energy density. Some work continues on the sodium sulphur couple. In the United Kingdom, where there is a continued interest in diesel-electric submarines, the Royal Navy has an active programme on the development of the lithium sulphur thermal battery as a secondary source, using the Li-Al/FeS couple. At the 5 - 10 hour rate energy densities of 100 - 130 Wh kg^{-1} have been demonstrated, and it may be found possible to increase this with improved electrode design. A cycle test of 2000 cycles over one year has been completed successfully. Even allowing for the high temperature requirement, this work could be of value in civilian applications of underwater technology. It is hoped that development will be completed in 2 - 3 years time. Other secondary sources, in which development is believed to be still active, include the thermal storage systems using carbon or magnesia blocks (70 - 100 Wh/kg^{-1}) and the superflywheel employing aramid fibres where energy densities of 30 - 70 Wh/kg^{-1} are claimed.

Most designers have successfully used secondary batteries, i.e. lead acid, nickel cadmium or silver zinc, in an oil-filled pressure compensated housing for deep ocean use. Problems have occurred due to the cracking of plastic cell cases, oil and electrolyte contamination, hydrogen degassing, the production of mercury vapour (silver zinc cells) etc. but it would appear that these problems and many more have been overcome during operational use and that there are no fundamental problems in the successful installation and use of such secondary batteries at depths down to 6000 m. With batteries included within the pressure hull of vehicles, particular care has to be taken to avoid any internal arcing or the production of harmful gases or vapours. Great care has to be taken over fast response fusing of both external and internal cells to protect penetrators and associated cabling in the vehicle. All circuits on vehicle power bus-bars require remote control circuit breakers, with status indication for the crew, and all cabling and control circuits should be adequately protected against high temperatures, high humidity and mechanical damage. Again, the necessary improvements in design have been successfully made through operational experience.

Ambient pressure electrical connectors continue to be a problem at all depths, and many users have converted to gland penetrators through pressure housings etc. to improve reliability. Solid state invertors are usually employed to provide AC control of thrusters and ancillary power services in vehicles. Certain problems have been experienced in the use of power transistors and silicon-controlled rectifiers in these types of circuit, where performance has not met the quoted 'book' figures. Many vehicles have included hydraulic power for main propulsion and other services such as manipulator control and the powering of work tools, and there are no basic problems in this area so long as reliable ambient pressure compensation circuits are used. In fact the distribution of power by oil or water hydraulic circuits is ideal for deep water use, it provides flexible and very controllable power to a range of actuators virtually independent of ambient pressure, and with a minimum of actuator weight and bulk.

We believe that it is important to encourage the development of LOX/JP-5 (or diesel oil) renewable fuel systems, for use in the 1000 - 6000 m depth range underwater. This includes an investigation of the satisfactory containment and metering of these fluids, and operational trials to evaluate their performance as energy sources in either closed Brayton cycle systems or in diesel and Stirling engines operating in closed or semi-closed cycle conditions (see next section). For secondary, or rechargeable sources, we believe that both block thermal storage and advanced flywheel designs should be evaluated and possibly further developed. Perhaps the potentially most valuable secondary source being developed at the present time is the lithium sulphur (lithium aluminium iron sulphide) battery which is being tailored to naval submarine needs. When more fully developed, in say 2 - 3 years time, it should be evaluated for civilian underwater applications, and any necessary modification made for operational trials in this field.

7.2 Prime mover and propulsion systems (29)

This section covers, potentially, a wide variety of prime movers and their associated propulsion systems. Comments made here refer particularly to vehicles included in sections 6.3, 6.5 and 6.7 (ROVs, and both manned and unmanned free-swimming vehicles), and also to underwater work and repair systems although these are not covered by the review in any detail.

Propulsion systems will be considered first, since this is not believed to be a critical area. Present vehicles are driven from AC or DC electrical power, or by hydraulic power, through mainly shrouded propellors. It is believed that either electrical or hydraulic systems can be made to function at 6000 m depth without significant technical development. For electrical propulsion at these depths, brushless squirrel cage (type) AC motors are likely to be preferred since liquid pressure compensation can be used with negligible efficiency loss and arcing problems. Hydraulic systems offer flexibility in layout and good speed control. They are at present in use to depths of 2000 m but comparable hydraulic circuit layouts could be extended to 6000 m by ensuring that the differential pressure required is kept constant by a compensating system. For thrust, propellors are preferred to direct thrusters since they provide better slow speed control. For fine control, large slow-speed shrouded propellors are best since they produce lower attendant water accelerations and velocities. Research is taking place on contra-rotating propellor designs which may give small improvements in control and efficiency. Vickers Engineering has produced a submarine propulsion layout which combines a wide range of operational modes from a small number of mechanical elements; these include direct prime mover drive with high or low gear ratio, battery powered motor drive with high or low gear ratio, direct prime mover drive plus simultaneous battery charging and battery charging without propulsion. Such a system offers a considerable reduction in weight and complexity compared with a conventional heat engine-electric system, and allows the prime mover to be run at higher speeds for greater efficiency, considerable benefits for deep sea vehicles with weight and volume limitations.

We believe that the present level of development of propulsion systems is adequate for vehicle operation in 2 - 6000 m, and that adequate levels of development will continue to be provided by naval and industrial interests over the next few years.

The range of prime movers which have been studied, and in some cases developed for underwater use, is large. It includes air, steam and gas turbines, and reciprocating heat engines. For deep sea use it is necessary to close, or partially close, the heat cycle and this plus fuel considerations place limits on the more realistic contenders. For reasons of cost, technical complexity, and safety we have not included in this review heat cycles in which nuclear or isotopic energy is a component, or which use potentially unstable reactants or fuels (see section 7.1). However, a number of closed cycles exist in which thermal or chemical energy can be used to power gas or steam turbines, some of which were developed prior to nuclear propulsion and some in conjunction with the United States space programme. These include the Walter cycle steam/gas turbine running on hydrogen peroxide and the Brayton cycle gas turbine employing fuel and an oxidant in a catalytic combustor.

There has recently been a considerable revival of interest in reciprocating engines running in closed or near-closed conditions. The closed-cycle diesel engine is again being studied in the United Kingdom, and Sub Sea Oil Services (SSOS) in Italy have developed an engine in which the exhaust is scrubbed by sea water, and the process is claimed to be depth-independent. (We visited SSOS and were shown this engine in its trials submersible by Dr. Santi). In Sweden, United Stirling has developed and tested a 25 kW Stirling engine which runs on diesel or methanol plus oxygen, and are at present testing a 100 kW version for the Royal Swedish Navy. (We visited Mr. Herbert Nilsson at United Stirling in Malmö). Both diesel and Stirling engines can be designed to operate on air and on oxygen, with efficiencies of about 30 - 35%. This would enable air to be used by a manned vehicle for surface cruising or schnorkelling, and so conserve the oxygen for underwater activities. Oxygen would best be carried in liquid form (LOX), and suitable cryogenic vessels have been developed to contain the oxygen for 3 - 4 weeks at about -170^{o}C (reference visit to Gabler S.A.).

Preliminary notes from United Stirling (from Mr. Herbert Nilsson) indicate that a Stirling engine could be run at a depth of 1500 - 2000 m through the addition of an exhaust gas compressor which would use some 10% of the available power at these depths. Since a Stirling engine has an external combustion chamber, certain advantages accrue over a diesel: the fuel mixture can be optimised to reduce exhaust products and the pressure in the chamber can be raised to facilitate exhaust discharge. The diesel engine must recirculate a proportion of the exhaust CO_2 as part of the working fluid but the major part has to be discharged from a low operating pressure, or a liquid scrubber used. It is likely that the high flame temperature in the combustion chamber of a Stirling engine will reduce carbon and other deleterious deposits. Radiated noise levels are considerably less than those of a comparable diesel.

There is a need to prove the satisfactory development of a medium power prime mover for underwater vehicles and work stations for deep water operations. We believe that Walter and Brayton cycle system/gas turbine systems merit further study, although these are likely to be costly solutions due to their engineering complexity and fuel requirements. They may also be limited by safety and operational considerations. Our recommendation is that a European effort should be made to prove the performance of closed cycle diesel engines, particularly the design developed by Sub Sea Oil Services, as well as the Stirling engines developed by United Stirling, for operation in water depths from 1000 - 6000 m. These tests should be designed to determine the reliability of engines and control equipment, their efficiency as a function of depth and the degree of combustion chamber and other fouling experienced under operational conditions. Such an investigation should also include a realistic assessment of operational fuel and oxidant requirements, including containment, metering, displacement loss compensation (for vehicles) and refuelling limitations.

7.3 Umbilical design (30)

Umbilicals, or cables containing power, signal and strain members, are critical components in a number of vehicle systems. They are crucial to the success of ROVs, usually also to bottom tracked vehicles and certainly to towed manned or unmanned systems. Possibly no other component gives more trouble, and the record of some ROV operations in particular has been a category of failures due to faulty umbilicals.

Over many years in oceanographic work, it has been found possible to develop simple electro-mechanical cables which can be used in depths of 6000 m and lengths of 10,000 m. These are usually cables covered with torque-balanced helically wound steel armour wires and containing the minimum of electric cores.

For most oceanographic purposes a single coaxial core suffices and this is laid along the cable axis. Simple 'logging' cables of this type, between 6 - 15 mm in diameter are relatively rugged and may be handled on properly designed drum or traction winches. The central coaxial conductor permits control and power signals to be put down the cable and multiplexed data signals to be returned. As soon as the cable is made more complicated, by adding small individual conductors of twisted pairs or quads, then reliability deteriorates.

Unfortunately, this message did not seem to get through to offshore operators early enough and many ROVs are still fitted with umbilicals containing a multitude of small electrical cores. It is quite common for operators to have to change umbilicals six or more times in a summer season. Recently there has been a move to change to partially multiplexed systems and this should certainly improve matters.

The problem is aggravated by the fact that there is little incentive for cable manufacturers to conduct proper umbilical development. Most designs are based on a particular manufacturer's experience with land cables, so there are now as many umbilical designs as there are ROVs and cable manufacturers. No manufacturer is prepared to give any form of warranty with the product. Two very important recent developments have already introduced further variables and unknowns. The first is the use of Kevlar, an aramid fibre manufactured by Du Pont, which, properly used, can provide the strength of steel at 5% of its weight in water. The second is the introduction of optical fibres into the umbilical to provide a band-width which will allow a digital rate in excess of 10^8 bits per second. These two developments are pivotal to the further development of ROVs, and any systems which depend on a strong buoyant tether and/or high telemetry rates for video. The problem will be to introduce these new components into a cable technology which is struggling to cope with the simpler problems which steel and copper wires present.

The most effective research and development in this field is being carried out by naval sources, and particularly the US Navy. Aramid fibres have potentially high tensile strengths but batch quality varies, and the fibres are prone to abrasion. Great care has to be taken in winding and treating tension members made of this fibre if reproducible and consistent tensile strengths are to be achieved. Furthermore, great care has to be taken in the design of cable section to ensure that abrasion is minimised and that an acceptable fatigue life in cycling is obtained. Rather than using the fibres as a loose braided yarn, it appears that both the US Navy and the Royal Navy are developing techniques for forming the fibres into coated tension members. In this way they get a product with a guaranteed, reproducible, tensile strength which can then be 'designed' into a strain cable using concepts of geometry etc. already developed and proved for steel cables. We detect a similar move by naval researchers in their treatment of optical fibres. At present no manufacturers of optical fibres will guarantee the drawn tensile strength of the fibre for lengths in excess of about 200 m, for most land-based communication purposes this is no great hindrance since finished cables will not suffer significant stress. So there is a move by the navies to develop protective and strain-bearing coatings for single fibres which raise their tensile strength from, typically, 1 kg to 50 kg. Even when coated, they may be no more than 1.5 mm in diameter and offer enormous signal advantages over the equivalent sized copper conductor. At this level of ruggedness they can be 'designed in' to a cable section in a similar way to the use of Kevlar.

Certainly there is a need for continuing work to be carried out on the development of umbilical cables, particularly designs making use of the advent of Kevlar and optical fibres. Controlled tests need to be initiated on the tensile and flexural properties of such cables, and the effects of high pressure on different types of lays. The organisation of a working group between the major manufacturers in Europe would be valuable, particularly if this led to the standardisation of proven cable designs for use in the underwater field. There is also a need to provide the necessary test facilities for these designs.

7.4 Manipulators and robotic tools (31)

Manipulators and their associated tool suites are an essential component for ROVs and manned submersibles. Considerable progress has been made over the past 5 - 10 years to improve their performance in underwater tasks. This impetus in development has been led by a wish to reduce offshore diving operations to a minimum, and by the great strides made in robotics and semiconductor industries.

Manipulators come in various forms and levels of complexity, from light open-framed rate-controlled types to more complex master/slave devices with proportional control and force feedback. The simplest system may cost in the order of £1,000 and the most expensive some £50,000. Electro-hydraulics is rapidly becoming the preferred method of control, it provides excellent controllability, small actuators and a system which can be made independent of depth. Recent advances have included the addition of microprocessor storage and control so that repeatable functions, whose co-ordinates are known, can be carried out automatically to reduce time. Such developments will be valuable in improving the range of tasks which can be carried out by ROVs.

Considerable advances have also recently been made in adapting diver-held tools for use by manipulators. In a sophisticated work system, tools have to be stored in a 'ready-use' tool frame which can be accessed by the manipulator. In the system developed by the US Navy, the manipulator 'hand' is supplied with an integral hydraulic supply and quick-fit connectors which automatically mate when the hand enters a tool bin on guides. At the same time the position co-ordinates of the hand are used to control the pan and tilt system of the viewing video camera via microprocessor control.

We believe that the present level of manipulator and tool development in the underwater sector is adequate for the likely needs of remote equipment in deep water. Such systems will continue to benefit from the large investments in robotics made in the nuclear and production industries. It should also be remembered that the cost of manipulators for use underwater is such that there is a definite trade-off between complexity and price which the users are prepared to make. Further investment in this area would be unlikely to alter the present trends or speed of development.

7.5 Video systems and video transmission (32)

High quality remote visual monitoring equipment is essential for the majority of underwater tasks in the commercial, military and scientific underwater fields. It is particularly critical for the continued development of ROVs, where improved operational performance will depend on simulating the environment at the surface in a more realistic manner.

For simple monitoring and some inspection tasks, it is adequate to have a relatively cheap closed circuit TV camera which may or may not be mounted on a pan/tilt device. For more elaborate work considerably greater sophistication is needed. For example, at the larger end of the ROV scale 'Consub 2' uses four cameras, one low light unit with pan and tilt capability for the pilot, a second pan and tilt for customer use and coupled to this, a colour camera with zoom lens for close up detailed inspection work. Even with this type of elaboration, including its attendant data transmission needs, the pilot does not get anything like the same information as a diver would get, or a submersible pilot with 180^{o} vision.

Practical considerations apart, the ideal would be to develop a system which would provide complete simulation of the environment around the ROV, with image fidelity matching the capabilities of the human eye regarding resolution, colour rendition and stereoscopy. However, the provision of such a display at normal TV refresh rate with say a 180^{o} by 90^{o} field of view would require a totally impractical data transmission rate, corresponding to hundreds of parallel 5 MHz display channels, which would not be economically viable using any known technology.

In the real world with limitations of cost, weight and data transmission rates, compromises will have to be made along the way in the development of the more sophisticated visual monitoring systems. Users will require improved low light cameras, such as developments of the silicon-intensified target (SIT) and the silicon diode vidicon cameras. They will also need some colour rendition, possibly in a high-resolution panel in the centre of the screen, and the provision of a useful field of view. Some measure of stereoscopy, both twin cameras and holography, would also be invaluable when conducting the more dextrous tasks. Since the data has to be provided in real time and its transmission is limited by cable bandwidth, the best design compromises are needed.

A considerable amount of work is now being undertaken in the UK and USA on optimising visual displays and on making the best use of limited band-width umbilicals. With the advent of fibre optic cores, part of this problem will be eased, but it will still be very important to continue research into optimal simulation, under instrument weight and cost restraints, to provide the future ROV pilot with 'realistic' vision to carry out difficult and sometimes delicate tasks.

7.6 Navigation, position fixing and track recording (33)

This is a subject which affects the operation of all the vehicle systems listed. Free swimming vehicles will require to navigate on known tracks, they will need to store position fixes and they will invariably need to be located. Cable lowered and controlled vehicles will need to have their position fixed relative to the surface platform from which they are operated.

The importance of navigation at the surface

Positioning objects implies a reference frame. In the simplest underwater case, that of equipment lowered vertically from a ship, the wire out indicator or metre-wheel gives distance along one axis, the geographical ship position the other two. In the most complex case, the geodetic track of a free submersible may be needed in all dimensions without any help from a surface ship. There is no publicly provided underwater navigation system with even a limited range facility, let alone world-wide coverage; hence the need for expensive inertial navigation on military submarines.

In between the two extremes above a wide spectrum of systems and techniques are available and in use today. In many cases acoustic positioning relative to a network of bottom moored beacons or transponders is used. Usually the network will need to be surveyed-in on a geodetic frame by a surface ship navigated by radio techniques. In other cases it is sufficient merely to position the underwater object by acoustics relative to the surface ship. Thus we see that, apart from the military submarine which is not our concern, surface ship navigation is crucial to practically all underwater navigation. Near shore, high quality, accurate radio navigation methods can be set up cheaply; further offshore Decca Hifix or Main Chain, or Loran C may be available in busy commercial areas; otherwise for the vast majority of distant open ocean areas OMEGA and the Transit Satellites provide the only world-wide, civilian all weather navigation systems at present. Omega has inherently low resolution and accuracy, whilst the disadvantage of the medium precision Transit system is the small number of fixes per day at non-uniform, though predictable, intervals. This feature becomes critical for example when surveying-in a deep ocean transponder network for which the tens of satellite fixes required take several days to acquire. For the future, the Global Positioning System (G.P.S.) promises geodetic surface ship fixing via satellites on a virtually continuous basis, which will speed up the surveying-in phase considerably. Also the geodetic accuracy of the G.P.S. will nearly match the good relative precision of underwater acoustic systems.

Underwater acoustic positioning

The most common way is based on interrogating transponders, but precision timed beacons, phase tracked CW beacons, hydrophone listening arrays, sonar beam scanning, doppler sonar and other techniques have been described for specific applications; indeed there are practically as many systems as there are underwater operators. The absence of any widely accepted industry standard on the market probably reflects the variety of apparently different applications and the fact that even the best implementation suffers degradation at times due to environmental factors, whilst cross comparisons are difficult and expensive to carry out.

Despite the variety, a few generalisations can be made. Resolution can be very good (cms) and maximum range can be large (1000 km), but the fundamental properties of acoustic propagation in the ocean preclude simultaneous achievement of both. Roughly, maximum range will be 10^3 to 10^4 times the range resolution. Absolute accuracy however is predominantly determined by uncertainties in the absolute average sound speed along the path of typically 0.1% to 1%, these errors thus considerably exceeding the resolution for ranges well short of the maximum. The internal consistency will be rather better being related to the fluctuations in path sound speed. Sound multipaths due to refraction and boundary reflections complicate returns, causing confusion for inexperienced operators and making it appreciably harder for the software of automated systems to cope. It is very important to appreciate that overall positioning errors are larger than the simple ranging error along a single path by a geometrical multiplying factor dependent on network angles. Long baseline networks have lower error factors than short baseline ones.

A ship with four or more transducers spaced around its hull forms a short baseline system with which to position free, towed or lowered vehicles. For deep (2000 - 6000 m) vehicles azimuthal uncertainties approach 1% of slant range. If only one hull penetration is available, a transducer array split into quadrants of order one wavelength apart forms a super-short baseline from which one can expect errors exceeding 1% of slant range. Here then is the challenge to system designers, to improve these short baseline systems to the 0.1% of slant range level, at which point the underwater uncertainty around 10 metres will match the G.P.S. surface uncertainty. There is enormous operational convenience in having the complete system on the ship and from not having to lay and survey-in transponder beacons. Since the error factor cannot be reduced, and the absolute sounding velocity may not be available, all effort must go to reducing the random ranging error in relative positioning; for example by transmitting over wide band-width from the transducers on the ship where high power is available, and by using hydrophones on the underwater vehicle so that good signal-to-noise ratios can be achieved. Then frequency and space diversity should be employed to counteract multipaths, and careful monitoring of ship motions, pitch, roll, yaw, heave, surge and sway will also be necessary if their transferred effect on underwater positions are to be filtered out. Finally since many underwater vehicles move rather slowly, positioning rate may be traded for precision by smoothing processes.

Long baseline systems will continue to be the best choice whenever activity extends over a long period in one area or when repeated site visits are expected or if the highest performance is required as in tracking ranges.

Autonomous navigation

Free submersibles working near the sea bed might well need autonomous navigation, but for rather shorter periods in comparison with military submarines. There may be merit therefore in combining lower performance inertial sensors with ground speed measured by doppler log, depth by pressure sensor, height over bed by acoustic altimeter and gyro compass to produce a workable dead-reckoned track. One aspect of the relevant technology which needs attention is the directional high frequency transducers for such deep submergence vehicles altimeter and doppler logs. Otherwise the electronics, processing, power requirements all seem well within present capabilities. One should not however underestimate the effort needed to put sub-systems into a reliable integrated navigation and communication package within a small deep vehicle, where failure of either may mean expensive loss for an unmanned system, and danger for a manned vehicle. There will also be a need for the advance warning of topographical changes and terrain following techniques should be investigated.

7.7 Buoyancy control and payload (34)

This subject is critical to the effective operating performance of ROVs and manned and unmanned free-swimming vehicles. There are three factors regarding buoyancy which need to be assessed:

1. The maximum payload of people and instruments and samples which can be loaded safely into the system and permit it to return to the surface.

2. The weight which can be picked up and put down by manipulators, either being transferred back to the sea bed or work site, or into a contained on the vehicle.

3. The number of times which the vehicle buoyancy can be adjusted to compensate for the operations in paragraph 2 above, or to speed ascent or descent.

Payload

At depths greater than 1000m the generation of buoyancy through the maintenance of gas spaces in equilibrium with ambient pressure would require an excessive quantity of stored gas or chemical energy. Thus all buoyancy on deep submersibles during the dive is either in fixed rigid material, usually syntactic foam blocks, or in empty pressure vessels. The syntactic foam required for depths to 6000m has a relative density which has improved from 0.67 to 0.55, and it has taken the US Navy and commercial companies 5 years to create this improvement. It is unlikely that further investment would result in a great increase in buoyancy of the material. The net buoyancy of enclosed pressure vessels could be increased by use of composites based on carbon fibres or possibly metal composites.

Payload would of course be greatly increased if the weight of the energy store and power generation system could be reduced. Since all the submersibles listed in Table 5 rely on more or less conventional secondary batteries, it is apparent that the weight of these is a significant factor in reducing the optional payload.

Where external experimental or working equipment has to be used from a submersible with a minimum payload, it is possible to attach buoyancy material to the tools to achieve neutral buoyancy. This has the added advantage that if the equipment has to be deposited and picked up again, the recycled buoyancy is kept to a minimum.

In order to achieve extra buoyancy in emergency, submersibles are usually designed so that heavy components such as the manipulator, batteries, variable ballast and trim ballast, can all be dropped using mechanical linkages which do not depend on an electrical power supply.

Variable buoyancy

Tasks such as water jetting, entrenching, rock-drilling, etc. may require the submersible or vehicle to be ballasted heavy on the sea floor. Tasks such as picking up lost equipment, obtaining rock samples or sediment cores, require additional buoyancy to be generated during the dive. In shallow water vehicles the variation of buoyancy whilst submerged can be achieved by venting gas into tanks, or allowing water into the tanks displacing the gas. However, at great depth, the volume of gas which would be required to do this becomes prohibitive. The system used in the early bathyscaphes, and in Cyana and the planned SM-97, is to carry a quantity of lead shot at the start of a dive, and to have some spherical pressure vessels which contain air at one atmosphere pressure. When an increase in weight is needed, water is admitted to the pressure vessels; when an increase in buoyancy is needed, lead shot is dropped. The sum total of buoyancy/weight which can be cycled during the dive is therefore fixed. In the case of Cyana, the pressure vessels have a capacity of 60 litres, representing 60 kg of total variable buoyancy. The total lead shot carried by Cyana is 100 kg. This provides a descent rate of 0.4 m/sec; when all shot is dropped, the ascent rate is also 0.4 m/sec. Soft buoyancy tanks, in equilibrium with ambient water pressure, are used to give extra buoyancy on the surface, but these are vented completely during a dive.

To trim for attitude during a dive, in the case of Cyana and SM-97 mercury ballast is pumped fore-and-aft between small ballast tanks and this mercury can be dropped to gain buoyancy in emergencies.

During some scientific and commercial work it is important to vary the depth by 50-100 or even 1000m, vertically during a dive. If such a variation were to be repeated more than once, it would consume a significant quantity of the available variable buoyancy on each cycle; thus thrusters would have to be used. Since the vertical thrusters are usually smaller than the main motor, and the surface area of the vehicle in the horizontal plane is large, this process is inefficient and consumes valuable stored energy.

The provision of adequate variable buoyancy during a dive is thus a strictly limited commodity in existing submersibles, and limits their working capacity.

Summary

The question of fixed and variable buoyancy may seem a minor aspect of deep submersible design, and one not associated with high technology. The solutions adopted by the successful deep submersibles are very simple in principle, and no alternatives have been tested. Alternatives are pumped water out of pressure vessels, consuming main engine power; gas generators, requiring a volume of expensive chemical stored energy; or a larger volume of light strong pressure vessels exploiting the present cycling principles. The first solution places emphasis on total stored energy; the second requires a special energy source; the third again places emphasis on new materials for pressure vessels.

Fixed and variable buoyancy limitations do place severe constraints upon the equipment which can be carried and the work which can be done by manned and unmanned vehicles, and improvements to these subsystems would be very beneficial.

7.8 Pressure vessel construction and testing and hull throughputs (35)

This discussion is mainly relevant to the vehicle types considered in sections 22, 24, 26 and 27, i.e. ROVs, unmanned and manned free-swimming vehicles and towed or suspended manned systems, but obviously does also reflect the needs of other systems which use pressure cases for the containment of instruments and gases etc. underwater. We shall be concerned with improved materials and designs to withstand the external, hydrostatic, pressure only.

Traditionally the design of submarine pressure hulls has centred around the ring-stiffened steel cylinder. Such a design is adequate for modest depths where collapse limits are set by Eulerian buckling considerations. In deep waters, however, between 2000 - 6000 m, collapse will occur when the yield strength of the hull material is reached in compression. With all contemporary materials this means that the shell thickness required to limit compressional stress will also ensure stability from buckling. The most efficient shape, in terms of weight to displacement ratio, for such deep pressure vessels is a sphere, and this has been universally adopted for great depths. Early submersibles, and some contemporary ones, have used steel of varying proof stress grades (HY-80 to HY-120) and strengths from 700 - 1000 MNm^{-2}, but there has been a recent conversion to medium strength titanium alloys containing aluminium, molybdenum and other additions. These have strengths of 760 - 790 MNm^{-2}, although higher strength versions are available, they tend to be susceptible to stress corrosion cracking and hydrogen embrittlement. Calculations show that with a safety factor of 2 on the above strength figures (purposely conservative because the quoted strengths have not been derated for impact damage, knotching, out-of-roundness etc.) a 2 m diameter spherical hull required for 6000 m in steel will be negatively buoyant and in titanium will be just positively buoyant. The equivalent cylinders in steel and titanium will both be negatively buoyant for 6000 m. In these design cases considerable additional buoyancy will be required by free vehicles to enable them to carry a practical useful load. Similar calculations made for carbon fibre reinforced composites, assuming a compressional strength of 760 MNm^{-2}, give a different picture, the weight to displacement ratios are 0.35 and 0.45 for a sphere and cylinder respectively, giving good buoyancy margins.

We believe that the performance of steel or titanium is inadequate for the design of free vehicles capable of operating for extended periods at depths approaching 6000 m. In order to provide for a realistic payload it will be necessary to develop pressure vessels in composite materials. Possible contenders include carbon and graphite resin composites and the metal composites such as Boron Tungsten and graphite reinforced aluminium which are under development. The hybridised systems involving carbon, graphite and Kevlar, together in an impregnated tape, and developed for the aerospace industry, should also be investigated. It will be necessary to undertake development programmes to assess the quality which can be reliably obtained in the lay-up and winding of large vessels, to invesigate the additional stresses in fibres due to end loadings and supports, and to carry out further work on the effect of high pressure sea water on fibre strength under cycling conditions. It may be necessary to consider ways in which such composites can be effectively sealed from sea water, particularly end sections and mating surfaces.

We believe it will be important to provide very much better habitability in manned submersibles of the future, which could be designed for extended operations at deep commercial or scientific work sites. In this context the cylindrical pressure hull is much more attractive than a multi-spherical design, e.g. the DSRV, of the same internal diameter. It may well be that with the use of efficient composites this could become a reality. What is also needed is a comparable improvement in viewing. A great deal of work has been undertaken by the US Navy in the 60's and 70's on the development of spherical sector acrylic windows and their mountings. It will be important to continue this work into the deep ocean so that the maximum field of view is available at full oceanic depths. The limitations of acrylic should be assessed and other materials, including glass/acrylic sandwich constructions, glass ceramic and chemically strengthened glasses should be investigated, developed and tested. Support mountings must also be developed which ensure even edge loadings under changing hydrostatic pressures. Aerospace firms should be able to contribute to both this work and the required developments in composite pressure vessel construction.

The effect of hull penetration through the new materials will also need to be studied. Methods of containment of potentially high stress areas around any pipe or cable penetrator must be understood, and 'finger' penetrators need to be developed to allow cryogenic liquids to pass through composites without causing any performance deterioration.

7.9 Data telemetry (36)

Data telemetry is essential for most vehicle types and highly desirable for the remainder; even an autonomous moon-lander vehicle is likely to require some telemetry to ensure that it is working correctly after deployment. The data to be transmitted is likely to consist of a mixture of vehicle housekeeping, instrument outputs, outputs from optical and acoustic imaging systems and a voice link. Historically, multichannel telemetry systems have developed from pure analogue techniques, with frequency multiplexing to allow multiple channels, towards all-digital systems. We shall assume that future requirements in this field will be met by all digital systems.

The data rate required varies over a wide range, which can be roughly divided into low, medium and high data rates as follows:

Data type	Rate, bits sec^{-1}	
Vehicle housekeeping	1	low rate
Geotechnical instruments	10^3	
Voice link	3×10^4	medium rate
Mixed scientific payload	10^5	
Slow-scan video	3×10^5	
Deep-towed multi channel	20×10^6	high rate
Seismic profiler		
Broadcast standard	10^8	
Colour video		

We are concerned with vehicle operating depths from 2000 - 6000 m, and slant ranges from say 2000 - 10,000 m may also be involved. At these depths and ranges use of electromagnetic waves is ruled out by the highly conducting medium. Transmission must be either acoustic or by a cable, where the 'conductor' in the cable may be either by conventional electrical means or by the use of a fibre-optic light guide.

The performance of acoustic telemetry systems is severely limited by the rapid increase of sound attenuation with frequency in sea water. This problem is exacerbated by technological factors which limit the percentage working bandwidth which can be achieved. The effect of this limitation is to force up the highest frequency of the acoustic signal, incurring higher attenuation than would otherwise be the case. Such systems also suffer from multipath interference effects caused by reflection from the seabed and surface. This can be a major problem in this type of application, particularly where some horizontal transmission is involved and source and receiver are likely to be near the boundaries of the water column. These difficulties can be mitigated by keeping the acoustic path as short as possible, by the use of directive transducers and by the use of coded signals in transmission bursts. However, even with the best designed systems, the practical data rates will be in the low data rate category. To improve the performance of acoustic telemetry in deep water it is important that efficient wide-band transducers are developed for use at great depths, that directivity is improved and further work is carried out on secure multi-frequency coding techniques with error detection. There is a considerable corpus of naval research in relevant fields, but it is often difficult to obtain.

Transmission of oceanographic data through cables of 7000 m length at a few thousand bits per second is already standard practice. To meet the majority of vehicle requirements, the cable length needs to be extended to 10,000 m, and the data rate increased by several orders of magnitude. In most cases the vehicle umbilical cable has to withstand substantial tensile loads. Under these circumstances the most efficient design is of coaxial form with solid propylene dielectric and external torque-balanced helical layers of steel or kevlar to accommodate these loads. Current oceanographic systems use well-logging cables of 6 - 10 mm diameter. The 10 mm wire, with an electrical core of 5 mm diameter, has 80 dB loss over 7000 m at 200 kHz. The received signal power may have to be as high as 10^{-8} W to overcome thermal noise and electrical interference so 1 W will need to be transmitted. With an upper frequency limit of 200 kHz the maximum data rate is 1.5×10^5 bits per second. Larger diameter cables would improve on this, but it is unlikely that cables in excess of 25 mm could be easily accommodated by the mother ships envisaged, such a cable could pass 10^6 bits per second. Such cables would be acceptable for medium data rates.

Recent attention has turned to optical fibre technology for use in umbilical cables. Using a graded index glass fibre, losses of the order of 1 dB/km are possible permitting bit rates greater than 10^8 S^{-1} to service high quality video needs etc. At this stage of development certain manufacturers of ROVs have introduced optical fibres into short length umbilicals on a trial basis. Manufacturers are reluctant to guarantee minimum tensile strengths of lengths greater than say 200 m due to manufacturing constraints. A great deal of work also needs to be done to determine the best 'packaging' of the fibre and its optimum form of lay in the umbilical to protect it from tensile or bending stresses. Proper testing procedures for different lays and for long lengths are required, backed by operational experience. This would require an elaborate and expensive development programme, although like the acoustic problem, there could be help from naval interests (see also section 7.3).

7.10 Human control, sensory data, feedback, piloting, data display (37)

Some bottom landing instruments do not provide any data until they physically return, and it is possible to envisage an untethered ROV which is completely pre-programmed through its whole working cycle until it returns to the support vessel. However, in the general case, there is a need to provide a human supervisor, either with engineering/housekeeping data, or with real time experimental or sensory control data.

During Subtech '83 it was stressed that (with the exceptions above) there is always a human being in the loop; whether in a pilot's seat in a submersible looking out through a port, in the control cabin of a ROV viewing video screens and numerical displays, or in a laboratory checking the real-time output of measuring sensors. The difference is the distance of the human being from the point of work, and the amount of data supplied (see also section 7.5 on video systems and 7.9 on data telemetry).

Where the pilot is operating a slow-moving submersible by visual methods, the design of the controls is akin to the design of an aircraft flight deck. Good forward vision is essential, and ergonomically designed access to all the important operating systems and emergency controls is required. The French solution (Soucoupe, Cyana, SM 97) has traditionally had the pilot and observer lying down on shaped couches so that their heads are close to the downward-angled viewing ports. This gives excellent vision through small ports, but limited access to controls unless the pilot lifts back from the porthole. Larger vehicles, especially those working in shallower water, where large hemispherical viewing ports are possible, may have the pilot and observer sitting in comfortable seats operating aircraft-type instrument arrays. Since deep vehicles are probably going to be limited to small viewing ports, the French lay-out may be inevitable. If a large deep-ocean vehicle were to be built, a sitting position would probably be needed, in order to be compatible with endurance, crew shifts, and communications between crew members. Forward and downward vision could be provided by a combination of portholes and video.

On a manned vehicle further data and feedback may be needed on attitude, position of tools, and manipulator forces (see section 7.4 on manipulators). Research was conducted in the late 60s and early 70s on integrated thruster controls to provide pilots with simple controls, good feedback, and data displays on attitude, especially in connection with the Deepquest and the DSRVs (Avalon and Mystic). In practice, submersible pilots can become adept at manoeuvring such slow vehicles with quite simple on-off switch boxes, and the successful manoeuvring of a vehicle - for example mating a DSRV onto a military submarine - depends as much on the regular and repeated experience of the pilot as on the sophistication of the controls.

For ROVs the volume and quality of data displayed to the operator is also a question of research and development. Where the submersible pilot can sense acceleration, deceleration, and rotation, as well as observe through the porthole with depth-perception and parallax, the ROV operator only has flat video images, and numerical or analogue displays of attitude and movement. In practice, operators work efficiently with the limited data, but considerable research is being conducted into the improvements which might be obtained by better data and realistic visual simulation. Various combinations of stereo-vision, parallax generation, wide-angle plus narrow-angle viewing, holography, etc. are being tried. Further ergonomic research is needed to quantify the working advantages in terms of speed and accuracy which can be obtained by the different systems.

With ROVs the problem of providing a sufficient data rate may be a significant factor, but with untethered ROVs the problem of data transmission for both control and experimental measurements becomes extremely serious. For video transmission by acoustic methods the highest picture rate is about 1 picture every 15 seconds, whereas the minimum picture rate for good control is 4 frames per second. Russell et al (1983 Subtech) suggest a tethered ROV communicating with a UROV over short path lengths of the order of 100 m, using 600 KHz transmissions with a data rate of 10^4 bits/s. This compares with a slow scan video standard of 3×10^5 bits/s. Even over these ranges there are problems with multiple path delays. Over typical oceanic ranges and depths of several kilometres, the frequency would be lower, and the data rate very much slower.

Russell also described techniques of bandwidth reduction for video data transmission, and suggested the use of artificial intelligence within the vehicle to reduce the volume of data which would need to be transmitted in either direction. Others have suggested a more complex structure, in which artifical intelligence is used in the UROV to manage the basic controls and data logging and an acoustic link is used to transmit a greatly reduced data and control signal volume to the support console; at the support console a second artifical intelligence system would be used to regenerate missing or condensed data for the operator, and also to take into account the time delay resulting from the acoustic transmission time. Such a system would have to be rigorously tested in realistic conditions to find out the best combination of 'intelligence' and data format which would provide the required degree of control.

Summary

This is a very wide-ranging subject which is particularly important for the control of ROVs and unmanned free-swimming vehicles (UROVs). Any solution will be a compromise based on the limited 'realism' of video and the modest or poor data rates of cables and acoustics respectively. In the case of UROVs it is quite conceivable that control will be lost on occasions when the acoustic path is blanketed by a structural member. For this and other cases it will be necessary to invoke the aid of artificial intelligence with a track memory so that the vehicle can control itself back to base. This type of advanced control, and the more general use of artificial intelligence at either end of a low bandwidth link, are being studied by groups in the UK, but more analysis is needed to select those lines of development which are most likely to succeed (see also sections 7.5 and 7.9).

7.11 Life support (38)

Life support is no more difficult in deep vehicles than shallow ones, although weight and volume restraints on the amount of oxygen and scrubbers which may be carried may make it more difficult to achieve objectives. Certification authorities (Lloyds, Det Norsk Veritas) lay down standards for air purity, breathing gas endurance, etc. Total hours of life support for crew is usually a minimum of 72 hours. Since the normal working dive for a small submersible is 5-8 hours, the 72 hour life support is designed to provide at least 2.5 days of working time to mobilise and carry out rescue operations in the event of a serious accident. This period was just sufficient in the case of the Pisces accident in the southern Irish Sea in 1974.

When a submersible is designed to be autonomous (for example Argyronête, Seahorse II) there must be crew watches, greater comfort, and suitable sleeping space. This becomes practicable at a minimum weight in air of about 40 - 50 tons. The life support and subsistence equipment becomes a small version of a military submarine. For example, the Bruker Seahorse II, which was completed in 1983 for work in shallow water, has a small galley, bunks, and toilet, as well as a small workshop for underway repairs.

Naval submariners are sceptical of the ability of companies or laboratories without military experience to manage and navigate safely with military type submarines. The combination of navigational and control discipline, operational maintenance and reliability, etc., places stresses on the crew for prolonged periods which are quite unlike those involved in traditional submersible operations. They point out that a 50 ton submarine cruising at the surface to recharge its batteries would be a very uncomfortable craft in anything but the calmest seas. In the development and operation of autonomous submarines or submersibles it would be an advantage to incorporate as much military experience as possible. Vickers in Britain and IKL-Gabler in Germany would be in a good position to provide the necessary expertise. For autonomous submersibles life support requirements should be based on naval principles.

7.12 Emergency and bale out systems (39)

No special investigation of emergency systems for deep ocean vehicles was made during this survey, but some general points can be made. In the event of buoyancy materials crushing, or buoyancy compartments flooding, and/or loss of power, the pilot should be able to drop sufficient weight to obtain strong positive buoyancy. Items to be dropped include batteries, skids, manipulator arm, shot ballast, trim ballast, etc.

A deep ocean submersible is, by definition operating deeper than the maximum depth for divers, and deeper than the maximum depth for all but a very few manned vehicles and ROVs. In order to maximise safety in emergencies, life-support time should be as long as possible, and the vehicle should be fitted with acoustic beacons powered independently from the main power sources. Recovery operations could only be carried out by the assistance of other vehicles. In the case of some combined experiments with Cyana and Alvin, either vehicle could have assisted the other. This circumstance is the exception rather than the rule. In general, if an accident occurred, one or more ROVs or manned vehicles, with the necessary support ships, might have to be transported many thousands of miles. In the case of the Irish Sea Pisces accident in 1974 ROVs and submersibles were flown from California, Canada, and the North Sea to a port in Ireland. The greatest delay was in steaming the support vessels back to the port, loading the vehicles and their support equipment, and returning to the dive site. In the event of an accident to a deep ocean submersible one thousand miles or more from land, this delay could be a week or more.

It is not possible to suggest easy solutions to these problems. It is reasonable to suggest that the life support for deep ocean submersibles should be significantly more than 72 hours, unless an ROV or another submersible with a similar depth capability is close to hand, or on the same support ship.

If an autonomous submarine were considered for deep ocean work, the safety problems created would be quite new. This analysis suggests that even if a deep ocean vehicle were designed for prolonged duration dives of several days, it should be supported by a mother ship with a deep diving ROV available. It should also be possible to provide a Gabler-type escape capsule on the larger design of autonomous submarine.

7.13 Surface support ships, platforms and handling systems (40)

Two opposing trends can be observed in surface support. Since the surface support ship is the most costly part of most submersible/ROV/Oceanographic operations, the first approach is to make the underwater intervention system as light and small as possible, and to try and operate from non-specialist vessels. At the opposite extreme, support ships have been built for submersible and ROV operations which utilise moon-pools and large stern A-frames and dynamic positioning in order to maximise the chances of launching, operating and recovering the vehicle regardless of sea state. A third, and very different option is to abandon surface support altogether, and conduct an autonomous submerged operation.

It is not possible to analyse these questions fully in this report, but their advantages and disadvantages will be summarised briefly below.

Light weight with ship of opportunity

The smallest submersible capable of diving below 2000 m is Cyana with a weight in air of 9 tonnes. A more typical weight is 15 - 25 tonnes. ROVs for deep water in most cases are linked to a cage or garage which more than doubles the weight of the actual powered vehicle; to this has to be added the control cable, cabin, and operator's console, which typically results in the all-up system weight being about 10 - 15 times the weight of the components which are launched into the water. Total on-board weight ranges from 3 tonnes to 30 tonnes.

In either case, a vessel of several hundred tonnes would be the minimum for support in a calm sea; to ensure safe launch and recovery in a rough sea, the vessel would have to be 1000 tonnes or more. Thus, where deep water operations are concerned, the search for cheap solutions must be somewhat illusory. Since deep water operations are bound to be associated with expensive research projects planned over many months or years, or with commercial activities involving very high down-time costs, the risk of conducting operations from an unsuitable vessel and losing a high proportion of on-site working time due to bad weather is probably too great.

Experience with UROVs is very limited, but since they do not require large cable winches, or on-line video and control systems, it is possible that they might be operated from conventional research or military vessels with a minimum of modification.

Specialist ship or platform

The most successful deep ocean submersibles have been operated from specially designed or adapted ships. Alvin dives from the catamaran pontoon vessel "Lulu"; Cyana is launched via large A-frames from CNEXO research ships; Deepquest has an extremely elaborate launching vessel with a floodable rear section. In shallower water the Pisces and Slingsby commercial vehicles working mainly in the North Sea and other European waters have all been operated from converted stern trawlers with large stern A-frames and modified deck space aft. Saipem operates submersibles, ROVs, and diver observation and saturation bells in the North Sea from special support ships with a moon-pool and A-frame such as the 5000-tonne vessel 'Ragnus Due'. Specialist semi-submersible mobile platforms have recently been introduced in the North Sea to support saturation diving, fire-fighting, salvage operations, and other emergency activities.

Specialist vessels with dynamic positioning, designed launch equipment, and excellent on-board maintenance facilities, laboratories, and data processing equipment are very expensive. Yet the return in the form of almost guaranteed operating time on site has proved compelling in the commercial world, to the US military, and in the US and French research sectors.

Most work by ROVs in water depths less than 1000m has been in support of oil-field operations or naval requirements. In both cases powerful and well-equipped work-boats, supply boats, survey vessels, tugs, etc. are generally available. Thus, although ROVs are routinely operated from vessels which were not designed to support them, the support vessels are substantial and have excellent power and back-up facilities. Since the ROV will require its own launch frame, cable and winch, as well as the control cabin and maintenance equipment, this is important. For work deeper than 1000m, as in the case of the Dual Hydra 2500 working on the Shell drilling operation off New Jersey in 1983, the ROV support was integrated into the deck equipment of the Discoverer Seven Seas, a dynamically positioned drill ship. The ROV was launched from its own A-frame, 5m above the water surface, and the cage-plus-ROV descended a taut guide-wire, (Frisbie, 1983).

For deep water work with ROVs in future it is probable that the best surface platforms will either be existing specialised support vessels, or specially built vessels designed to support underwater intervention vehicles.

Autonomous vehicles

Some analysts have concluded that since cheap surface support is not reliable, and good surface support is very expensive, the best solution is to work completely submerged. The arguments concerning safe and economic operation of non-military autonomous submarines are complex and unresolved. However, assuming that efficient and economic vehicles of 50-500 tonnes could be operated to depths of the order of 1000-2000m, they could logically form ideal launch and control platforms for either ROVs, or smaller and deeper working submersibles. The logic of this depends upon whether it is really cheaper and more efficient to support the smaller system from a submarine which is free of wave action, or from the sea surface. This kind of "piggy-back" system might be tested first under ice in the Canadian Arctic. Haas and Kern (1983) state that a 46 tonne 460m depth vehicle can be built for autonomous work at a cost of $3 million, and that a deeper and larger vehicle could be built for £4 million. This is an order of magnitude less than a dynamically positioned purpose-built diving or submersible support ship.

7.14 Land, sea or air transportability (41)

Deep ocean submersibles typically weigh 9-50 tonnes in air. ROVs with support equipment, typically weigh 4-40 tonnes for work below 1000m. The UROV Epaulard, weighs 3 tonnes. Bottom landers typically weigh a few tonnes, or less than 1 tonne.

Ease of transportability is an important factor in ensuring effective and economic use. This includes consideration of transport by road, rail and air, as well as cranage for lifting onto a ship, and launch and recovery at sea.

The DSRVs (Mystic and Avalon) each weigh 25 tonnes, and can be transported by air in large military aircraft, and by road. A trial was conducted in the Clyde in August 1983, when a DSRV was flown from San Diego to Prestwick, and then transported by road to Coulport on the Clyde. The DSRV was then mounted on the RN Submarine "Revenge" for diving exercises (Guardian). The Swedish Navy rescue submersible built by Kockums Varv weighs 50 tonnes, and is road transportable. Pisces submersibles weighing of the order of 10 tons have been air transported on several occasions.

Although data have not been obtained on the absolute maximum weights and dimensions of cargoes which are air transportable, the above figures provide guidance. SM-97 is clearly air-transportable at 18 tonnes, and is is reasonable to assume that deep ocean submersibles carrying 2-3 men on single dives could generally be air-transportable.

The DSRVs and the Kockums Varv vehicle only carry on-crew personnel for short periods during rescue operations. Thus they cannot be taken as examples of multi-watch autonomous vehicles. The Bruker Meerestechnik Seahorse II at 46 tonnes is rail transportable in Europe (Haas and Kern, 1983) and can be handled by harbour cranes. Larger vehicles such as Argyronête or some of the larger high speed submarines proposed by Dr. Santi (SSOS) are clearly not transportable by rail, road or air. It seems probable that a long duration multi-watch deep ocean submersible would have a minimum weight greater than 100 tonnes and would therefore only be transportable on a ship, under its own power, or be towed. It is notable that the Kockums Varv rescue submarine has been designed for towing submerged to the dive site.

The NR-1, the only deep water autonomous research submarine at present operating, is 400 tons, and only mobile in the sea, although some cranes could lift it onto suitable ships or barges.

Bottom landers, towed instruments and ROVs will receive maximum utilisation if they can be operated from existing research ships using existing A-frames and deck machinery.

7.15 Maintenance problems (42)

This is a subject which affects the reliable operation of all the listed vehicles. It is an area in which military expertise is important, particularly in the case of manned submarines, and one in which new materials have an important contribution to make.

With any piece of underwater equipment one of the crucial factors is the degree of corrosion in sea water. Sometimes this is minimal with the careful use of compatible materials but usually some form of cleaning, inspection and replacement schedule will be required. BOM have said that the biggest maintenance problem with the submersible Cyana is due to corrosion, and a great deal of stripping, inspection, cleaning and renewal is required. This echoes our own experience in the oceanographic field. Design criteria for minimising corrosion underwater are understood and used by engineers, but sometimes a degree of corrosion has to be accepted. Newer materials such as the light titanium alloys, and the high-strength nickel-chromes such as Inconel, have helped greatly to reduce corrosion and maintenance in critical parts of underwater equipment. This includes personnel and ballast spheres for manned submersibles, acoustic release systems for autonomous 'moonlanders' which may stay on the ocean floor for a year, and highly stressed components such as shafts, bearing pins etc. Further improvements are likely with the introduction of advanced composites.

A submersible with the majority of sub-systems outside the pressure hull must be lifted out of the water for most maintenance. A submarine of conventional military configuration can be largely serviced from inside the hull. Craven (1977) points out that the conventional military design, with the main engines within the hull, requires a rotating propellor shaft penetrating the pressure hull, and this is a serious source of weakness. The smaller designs of Dr. Santi at SSOS have hydraulic motors outside the pressure hull, but his larger designs are strictly of military submarine configuration with large stern glands.

Summarising, we can say that careful design, and the application of improved materials, can go a long way to reducing maintenance problems on all underwater vehicles and instrumentation. In the case of autonomous submarines or submersibles a particular need exists to ensure that critical maintenance can be undertaken by the crew during cruise conditions.

7.16 Scientific instruments for use with the vehicles (43)

In the widest sense of the word, 'scientific' instruments are required for use with all the vehicle classes previously listed, and by all users. The range is very large, and it is not possible, nor is it necessary to list the devices and their applications here. Rather the section will be briefly concerned with particular needs or problems associated with the operation of such instruments on vehicles intended for the deep ocean.

The pace of work with advanced instrumentation for commercial, military and scientific use has increased rapidly over the past decade, partly fuelled by the offshore developments and also by radioactive waste disposal research. Commercial users require high resolution optical and sonar sensors, cathodic protection instrumentation, pipeline survey profilers and a host of other instruments. The military requires search equipment to be used on their deep ROVs and submersibles, particularly side-scan sonar and magnetometers. The scientific community requires a large range of devices to cover research at all water depths and the ocean floor, for the biological, geophysical, physical, geochemical and geotechnical disciplines. The specification of these instruments is largely initiated by direct user needs, and there exist adequate research and development resources in civilian and military laboratories and in industry to service this demand.

Perhaps the area which has seen the most rapid development of true scientific instruments is in benthic research at or near the floor of the deep ocean. This work has been largely supported by the need for scientific knowledge of the problems associated with high level radioactive waste disposal. This has involved all the scientific disciplines mentioned above. It has required the development of a range of instruments to measure temperature, pressure, oxygen, radionucleide diffusion, heat flow, sediment permeability and porosity etc. with a laboratory precision at depths of 5-6000m. In addition, a range of sediment and pore-water samplers have been developed. Many of these devices are used singly, or in small suites on autonomous 'moonlander' vehicles, and problems of energy and logger capacity may be involved. In some cases, such as in the US Rhode Island ISHTE soil mechanics project, the frame of the device may be large, up to 5m square, and contain a range of sensors to service a particular in situ experiment. ISHTE stands for 'In-Situ Heat Transfer Experiment', and apart from the main (plutonium) heat source, contains a number of temperature, pore-pressure and shear stress probes, and can also provide sediment cores on command.

On mobile vehicles the main need is for improved geophysical and navigational sensors. This involves the development of efficient narrow beam acoustic transducers and arrays for use at great depths; also the development of wide-band transducers for seismic and navigational needs; and developments in the magnetic and gravitational instrumentation field for geophysical measurement for mobile vehicles. Improvement in the navigation and position fixing of deep vehicles will largely depend on improvements in acoustic technology, and there is an urgent need to develop systems which integrate the data for available positioning and velocity sensors into the best 'dead reckoning' package. Inertial navigational systems need also to be studied in this context to see whether they can provide, at more modest price and precision than their military counterparts, an input to the deep ocean navigation problem.

7.17 Scientific data recording on the vehicle (44)

The degree of dependence of the different types of vehicle on scientific data recorders on the vehicle is estimated below.

	Vehicle	Degree of dependence
Type (20)	Bottom landing static systems	9
(21)	Cable lowered bottom lander	2
(22)	ROV	3
(23)	Bottom tracked mobile vehicles	0
(24)	Unmanned free-swimming vehicles	7
(25)	Towed unmanned systems	8
(26)	Manned free-swimming vehicles	3
(27)	Towed or suspended manned system	1

There are a number of requirements common to these applications which may be summarised as follows:

(a) high data capacity per unit volume (all types),
(b) high data capacity per unit weight (especially types 20, 22, 24, 26),
(c) low energy consumption per unit of data recorded (especially types 20, 24),
(d) low quiescent power consumption (especially type 20),
(e) high data capacity per recording module - e.g. per tape (especially types 20, 22, 24, 25),
(f) high reliability (high MTBF) and low error rate (all types),
(g) high data rate (especially types 22, 24, 25, 26).

The requirements of most situations can be met, with a varying degree of success, bu the use of one of the following types of magnetic tape recorder:

(A) instrumentation recorder (multichannel DR or FM),
(B) low rate digital recorder,
(C) high rate digital recorder,
(D) video recorder.

Other media which may be appropriate in some circumstances are:

(E) magnetic bubble store,
(F) semiconductor store (PROM or battery backed RAM).

Of the above types, it may be argued that (D) is not strictly a scientific data recorder in the strict sense of the phrase. However, video records of sea bed structure and benthic life forms are considered to be scientific data for the purpose of this survey.

Limitations of recorders

(A) Instrumenation recorders

This type of recorder is best suited to recording signals with a bandwidth of up to 100 Hz, or so, from a limited number of sources, typically a maximum of 14 - over periods of a day or so. Apart from some special units developed for aerospace applications, commercially available units are generally bulky and have a high power consumption. Whilst some special purpose units have been developed and used successfully for sea bed seismic recording (i.e. vehicle type 20), the main use is in manned submersibles.

(B) Low rate digital magnetic tape recorders (up to 10^3 bits/s)

This type of recorder generally uses tape cassettes or cartridges although, occasionally, reel to reel recorders are used. Whilst the former are small and consequently suited to incorporation into deep sea vehicles or instrument housings, the total capacity is limited to about 15 Mbits (in the case of cassettes) at the present state of the art. Cartridges offer considerably more - up to 250 Mbits at the present state of the art - but drives and electronics suited to this type of application are only now becoming commercially available.

The principal area of use for these devices is in autonomous "moon-landers" although they are likely to be found in all of the other vehicles where operations involve scientific data collection. Reliability and power consumption are acceptable.

(C) High rate digital magnetic tape recorders

Where a high data rate is inevitable, as in the case of optical imagery, and digital storage is required, there is little alternative to the use of ½ inch reel to reel drives although modifed video recorders have been used. In the case of acoustic imagery (e.g. sidescan sonar), cartridge drives are adequate. The size of ½ inch drives is a severe obstacle to their use in deep sea systems. The requirement is, fortunately, not a pressing one.

(D) Video recorders

There is a wide range of devices available on the professional and consumer markets. Whilst reliability is not as high as for the data recorders mentioned above, it is probably adequate. Pressure from the professional and consumer markets can, in any case, be expected to result in rapid developments in this area. The main application is in free swimming submersibles.

(E) Magnetic bubble stores

In selecting a storage medium for any underwater system, a solid state device has obvious attractions in removing any mechanical source of unreliability. For high data capacity, magnetic bubble stores offer the largest capacity per module (typically 1 Mbit) with prospects of increase to, perhaps, 16 Mbits as new manufacturing techniques are perfected. They offer rapid access and high data rate (e.g. 10^5 bits/s) in a rugged device but power consumption is such that, in autonomous vehicles, they would require operation in a burst recording mode. For some systems where their data capacity is adequate, they may provide a suitable solution. Development, whilst relatively slow after their introduction, when a number of manufacturers dropped out, has regained pace - probably on account of interest as an alternative to mini computer floppy disk drives.

(F) Semiconductor stores

The commercial pressure for development is much greater in this field than in the bubble storage field due to the enormous market. There are two catagories of semiconductor store suitable for data storage: the PROM or programmable read only memory which is non-volatile, retaining stored data for 10 years or more even when powered down, and the RAM or random access memory which must be continuously powered by a back-up battery so as to retain data. These devices can be made using a number of semiconductor technologies but MOS devices are the most common by far. PROMs, whilst having the advantage of non-volatility, are not so easily addressed as RAMs and this limits their data acquisition rate appreciably (typically to 200 bytes/s). The state of the art erasable PROM is currently 256 kbits in NMOS technology with a power consumption of approximately ½ watt (100 mW on standby). This is rather lower than the equivalent bubble memory consumption; being non-volatile, the device can be completely powered down when idle. The CMOS technology offers very much lower static power consumption but lower capacity per device at present. In the case of RAM, the highest capacity CMOS device at present offers 64 kbits with a power consumption of 200 mW (10μW on standby). At around £600/Mbit, the price does not compare favourably with magnetic tape drives except for low volume storage applications but the simplicity and ease of data recovery are strong points in favour of the solid state solution. In addition, prices can be expected to drop considerably in accordance with previous experience.

Another data storage technology which is still in its infancy is optical disc storage. Since this, at present, employs rotating components, it may be only worthy of consideration when very high capacity is required, e.g. 10 Gbits. If an optical memory is developed with solid state addressing (i.e. beam steering), this will revolutionise storage techniques. The impetus to achieve such a device is, of course, already present from the computing industry which requires it for archival purposes.

Summary

We have considered above the limitations of various media currently in use, or projected, in relation to the requirements of various types of scientific and quasi-scientific data recording. The most serious problem identified has been that of obtaining sufficient data storage capacity in a volume restricted by practical mechanical considerations, together with a limited energy budget. Magnetic tape drives are operating near the limit imposed by properties of the tape and even the introduction of metal tapes and vertical recording will only allow relatively modest improvements in the future. It is hard to foresee what limits will be reached in solid state devices but, over the next 5 years, one would hope for an increase in capacity per device of 4-10 times together with a very considerable reduction in price. What is certain is that solid state logging will become progressively more attractive, for some applications, even though is is unlikely to displace tape for high capacity requirements. There is little purpose in any independent R & D work in this field at the moment.

7.18 Hydraulic, electrical and mechanical components (45)

The development of suitable components has a bearing on the successful operation of all the classes of vehicle listed. It is not possible here to carry out a survey of these elements of hydraulic, electrical and mechanical design, except to underline certain areas where they could usefully be improved or new development undertaken.

Most such components are adaptations of circuit elements used on land, sometimes these adaptations are successful and sometimes not. It would be far too expensive to consider developing specialised hydraulic components for use in underwater vehicles so it will always be necessary to adopt existing valves, pumps and motors. So long as care is taken over material compatibility, and regular servicing schedules are drawn up, then there would appear to be no great obstacle to the continued use of such components to greater operating depths. The effect of hydrostatic pressure in itself is no problem since hydraulic circuits can be designed to run at a given pressure differential above ambient, but care must be taken on vehicle ascent to ensure that suitable oil venting circuits are provided, otherwise the system will be ruptured. Similarly, great care must be taken with hull penetration to ensure that pipe seals are developed which will withstand the considerable pressure and temperature cycling which will occur in deep submergence operations.

The development of underwater electrical components, particularly connectors and glands, has had a long and somewhat unhappy history. Military users have tended to go for oil-filled glands, junction boxes and battery cases, even though this can result in time-consuming servicing schedules with a number of different oils involved. Certainly if the utmost reliability is required, and payload is a problem for deep submergence, this is a sensible way to go. However there is a lot of advantage in one atmosphere junction boxes and electronic cases etc. from the point of view of fast servicing, and with the advent of high strength aluminium, and titanium and composites the payload penalty for deep operations may be acceptable. Non-hoseing electrical glands are the best where the utmost reliability is required, or high voltages or currents have to be handled, but again they are a distinct disadvantage when vehicle servicing has to be undertaken. There are a range of underwater electrical connectors on the market, and have been for many years, but most of these suffer from one or more recurring defects which may be brought on by flexing or moderate voltage levels etc. We know of one leading UK submersible manufacturer who has been driven to obtaining the necessary level of connector reliability by manufacturing his own. It has also been necessary for IOS to produce its own polythene non-hoseing glands to guarantee the integrity of the electrical harnesses on the long-range side-scan sonar vehicle GLORIA.

A number of mechanical components used in underwater vehicles are likely to be land-based designs or adaptations of them. So long as proper criteria are followed, particularly galvanic potential compatability, there may be no great problems. However, there are now light and strong metal alloys available for underwater use which have a virtually indefinite life and it will often pay well to redesign components in such materials. IOS has recently stipulated that all users of the IOS acoustic release system who intend to leave instrument moorings or autonomous systems on the ocean floor for 6 months or more must purchase the titanium version of this system. Present returns show no corrosion after mooring deployments of 6 months to a year. We have also used the nickel chrome alloy Inconel 625 for mooring loadcell pins on an ocean data buoy which spent four years in the north Atlantic, and these underwater pins have been returned as good as new.

The availability of composite materials such as carbon, graphite and kevlar fibre laminates for pressure vessels will require test and development work to ensure compatibility with hydraulic, electrical and mechanical components and penetrators. It will be important to ascertain the best method of ensuring strain compatibility under changing hydrostatic pressures and temperatures. It will also be necessary to examine the stress changes which could occur in such pressure hulls due to the different methods of mounting external and internal components.

7.19 The use of on-board computing and microprocessors (46)

Although this topic has been listed as a separate sub-system, computers and microprocessors will, in general, be associated with some of the other sub-systems listed. With the possible exceptions of vehicle types 26 and 27, stand-alone computers will not feature appreciably, if at all, in the vehicles considered. There is, however, great scope for the use of micro-computers dedicated to particular applications. In particular they can be used in the following sub-systems:

(29) propulsion control,
(31) control of manipulators and tools,
(32) video signal processing and compression,
(33) navigational computation,
(34) buoyancy control,
(36) data multiplexing and telemetry,
(37) vehicle control systems,
(44) data compression prior to recording.

As a result, microprocessors have applications in all the vehicle classes listed:

(20) Autonomous "moonlanders". They can be used to control the experiment. This can include the deployment and actuation of probes, the control

of sampling to maximise the useful data acquired with a limited amount of storage, e.g. conditional sampling to record seismic events, high current flow, camera film advance etc. Also signal processing to reduce or compress data prior to storage or its transmission via a telemetry link.

(21) Cable lowered bottom landers. They can be used in telemetry equipment to allow control and data transmission of multiple signals via a small number of electrical cores in the cable (multiplexing - see section 7.9). Another use is in video signal compression.

(22) ROVs with umbilical control. Similar applications to the previous type of vehicle. Also to be used for navigational processing and improved vehicle control. Can provide response optimisation for actuators and manipulators.

(23) Bottom tracked vehicles. Possible uses for control, navigation and video signal compression or enhancement.

(24) Free-swimming unmanned vehicles. Uses similar to those given in 22 above. Also possible use for intelligent response to internal or external influences, e.g. adaptive control of acoustic telemetry and scanner information, track storage and initiation of navigational commands.

(25) Towed unmanned vehicles. Use for video and data processing and compression prior to telemetry. Also vehicle controls and navigation.

(26) Manned free-swimming vehicles. Many applications including those in navigation, data quality, housekeeping, propulsion, buoyancy etc.

(27) Towed or lowered manned system. Similar uses to those in 26 above.

Microprocessors have recently made possible the achievement of tasks which were previously thought to be impossible or impractical. The extent of their applications in underwater technology is sure to increase, being limited more by the necessary time and skills required to define the objectives and develop the software than by the state of the technology and availability of hardware. In the foreseeable future it is difficult to imagine that availability of suitable hardware will be a limiting factor, due to the massive impetus given to the semiconductor industry by military and commercial competition.

A particularly high standard of analytical ability and software expertise will be required to design intelligent systems for use when telemetry performance is limited; this would apply to the control of, and video reception from, unmanned free-swimming vehicles.

8. ANALYSIS OF FUTURE REQUIREMENTS FOR REMOTE VEHICLES

The need for the further development of each vehicle type listed in section 6 is briefly analysed here, including likely sources of future development and whether a European level of investment and effort is required.

8.1 Bottom landing static systems (20)

Free-fall systems are, at least at present, entirely of scientific application. They are already being developed to a sophisticated level to support biological, geophysical, geochemical and geotechnical research in the deeper parts of the oceans. The research undertaken is important to an understanding of many processes, including those controlling life in the ocean, the movement of the earth's crust and the origin and stability of sedimentary layers. It has applications relating to the disposal of radioactive waste, to deep sea mining, to petroleum prospects on the continental slope, to ocean circulation and climatic change.

Scientists working on these subjects agree that more elaborate systems will be required and that there is scope for development. Future bottom landing devices may include some of the following developments:

1. An increase in data storage. The ability to access that data remotely by a vehicle or suspended system, or by the use of a fibre optic link to the surface or by the release of a data package to float to the surface on command.

2. Greater use of microprocessors in intelligent systems to recognise events, and initiate operational and recording action to optimise the available visual and scientific data storage.

3. Improved energy storage, to allow for longer duration and to permit the use of mechanical processes, more powerful lighting, the operation of traps and samplers etc. The possible use of energy recharging from mobile vehicles.

Advanced bottom landers are highly specialised, and will probably be built by research institutes, or consortia of research institutes. Since the applications are so specialised, there is little opportunity for a European initiative to contribute to the design of a complete system. On the other hand, aspects of the use of artificial intelligence, submarine fibre-optics and power sources are common to these and other deep ocean systems and could benefit from specialised research.

8.2 Cable lowered bottom lander (21)

Cable systems are used in the offshore industry to lower heavy work tools and machinery for structural and pipeline repairs, and many other tasks. Robotic devices using cable guides are also being developed for inspection and maintenance work on deep modules. In scientific research cable, or rope, lowered landers are used for geophysical, geochemical and geotechnical sampling where weight is needed to drive corers and probes into the sediments.

These systems are likely to remain highly specific to single tasks, and to be developed by the companies and institutes most concerned. Since they depend on surface support from a ship or platform, usually with sophisticated handling equipment, they are expensive to operate, but do not require the autonomous energy, data storage and self-management built into free-fall systems.

The technology will probably evolve to cope with specific engineering and scientific needs in deep water. There does not seem to be scope for European-scale involvement in this sector.

8.3 Remote operated vehicle (ROV) (22)

Remotely operated vehicles with cable control have evolved extremely rapidly in the last decade, but there is no sign that a slowing in development will take place, either in requirements or performance.

ROVs are used mostly in support of offshore oil activities, and have also been developed for military purposes. The range of tasks now performed is remarkable, in variety, complexity and reliability. ROVs have become a work-horse of the offshore industry, displacing divers and manned submersibles and bells for a wide variety of continental shelf tasks. Whilst ROVs working below 1000 m are relatively few in number, developments such as the Dual Hydra 2500 (Frisbie, 1983) which is designed to work to 3000 m, show that the offshore industries anticipate working at great depths. In this report we project exploration drilling to 4000 m and production to 1200 - 1800 m by 1995. ROVs will definitely be required to carry out sophisticated work to these depths.

Future ROV systems will require some of the following technical developments:

1. Further development of master/slave positional and force-feedback manipulators to perform delicate and dextrous tasks.

2. Further development of modular work frames and tools so that vehicles can be adapted to a wide range of different tasks.

3. Utilise sophisticated video-imaging to produce wide-angle peripheral vision, high resolution central viewing and the addition of stereoscopic or holographic viewing when required.

4. Develop sonar imaging and pattern recognition procedures to give longer range pictures of the surrounding situation.

5. Develop umbilical technology to include fibre optic cores in strain cables in a proven and fully reliable manner.

6. Develop techniques for the use of free-swimming UROVs in conjunction with ROVs, particularly for work in confined spaces.

In this rapidly expanding industry, backed by commercial, military and governmental interests and resources, it is difficult to identify specific areas of development which would benefit form European scale investment and research. Probably the most useful areas would be:

1. Improvement and possible standardisation in the mechanical design, manufacture and testing of umbilical strain cables containing fibre optic cores for deep ocean use.

2. Development of visualisation techniques for the better control of ROV work tasks, and of techniques to improve the range and resolution in video and photographic surveys.

We also believe that there is a need to consider the development of an ROV system with a cage or garage for use in scientific research in the deep ocean. This would have applications in servicing autonomous benthic stations, in taking precise samples and cores, in reoccupying a previously studied point, in examining and releasing inactive scientific instrument moorings and as a stand-by rescue tool for European deep-diving submersibles such as Cyana and SM 97.

8.4 Bottom tracked mobile vehicles (23)

These systems will be used mainly for cable burial and possibly pipeline repair work on the continental shelf. We found that as a future development they attracted minimal support from industry and scientists concerned with deep water activities. The only exception could be from consortia interested in manganese nodule mining, where projected schemes include a heavy sea bed section which is dragged or propelled across the ocean floor. If such machines were designed there would only be a few in the world, and they would be developed by the major industrial consortia which have already invested in this area (see section 5.4). The major mining companies consider that investment in the commercial production from manganese nodules will not start within the next ten years, due to economic and political constraints.

8.5 Untethered, free-swimming, ROVs (UROV) (24)

Busby (1981) identifies only 3 UROVs capable of working below 1000 m. These vehicles have enormous theoretical potential in geophysics and physical oceanography (see sections 5.17 and 5.18) but are at present constrained by some daunting physical and technical obstacles. We believe that major investment in this area could produce valuable scientific results on a European scale. The present, prototype, vehicles suffer from considerable limitations. These are:

1. Limited energy. This not only limits range, but also affects the ability to operate sensors which could be carried such as: sidescan sonar, swath-mapping sonar, sub-bottom profiler, doppler sonar, magnetometer, CTD and cameras.

2. Limited payload and buoyancy control. This is partly due to the present size of the vehicles.

3. Poor terrain following and poor altitude, trajectory and attitude control.

4. Limited acoustic bandwidth for the transmission of data and control signals.

5. Limited on-board data storage.

We understand CNEXO-BOM at Toulon are working on the development of a super-Epaulard with thrusters to control the attitude at slow speed, more sophisticated forward sonar and automatic trajectory response, sidescan sonar and slow rate TV image transmission.

All the above factors which limit the present performance of untethered ROVs are susceptible to research investment, and many of the relevant engineering topics have been discussed in section 7 (see 7.1, 7.6, 7.7, 7.8, 7.17 and 7.19). A concerted programme of research could be launched to remove or ameliorate these limitations and to design a vehicle of advanced performance for use throughout the water column to a maximum depth of 6000 m. Such a major programme would include sub-programmes on integrated navigation, the control of trajectory, altitude, attitude and obstacle avoidance by means of artificial intelligence, the development of higher density energy storage and improved pressure vessels and buoyancy control.

A case exists for investment in such a programme bringing together expertise from several European institutions and manufacturers. At the moment there is little or no commercial development in this sector, although the value of removing the umbilical has been fully appreciated by ROV operators. The lack of commercial research in this subject is a reflection, probably, of the real complexity of the problem, the high investment needed, and the high level of effort already being devoted to improving ROVs. Thus a development which would probably start with scientific objectives, could result in great commercial benefits.

8.6 Towed unmanned systems (25)

These systems are already being developed to a sophisticated level by major research institutions. Further development and improvements are certain, but they will probably not be radical. Towed systems will be adapted to include multiple vehicles such as PARC-ERIC (one vehicle with lights, the other with cameras) and will benefit from the development of wide-bandwidth telemetry when cables with fibre optic cores are proven and by improved visualisation techniques. The number of users for such systems is limited, and the necessary development investment will come from scientific and military sources. We do not foresee a major European component in this type of vehicle.

8.7 Manned submersibles (26)

From our discussions with geophysicists and biologists in Europe, it is clear that there is a scientific interest in the use of a manned submersible capable of working down to 6000 m. In geophysical and geological studies it would be used particularly in rugged terrain to sample rock exposures and to examine the vertical stratigraphy. It could assist in the placing of long-term seismic stations and also bench marks for geodetic surveying. More precise gravity measurements are also possible and such a vehicle would be particularly valuable for under-ice surveying and seismics. Biologists also believe there is considerable potential for such vehicles, given an improved payload, better endurance and more comfort and visibility than present vehicles. A submersible could be used in the preliminary phases of many bottom experiments on productivity, migration etc. and to subsequently service such experiments. There would need to be adequate buoyancy control and the ability to move up and down through a range of 500 - 1000 m to monitor vertical migration. We believe users in the military and commercial fields would also value the availability of a vehicle with this performance.

At the present CNEXO-BOM are constructing a submersible, SM 97, which will have the capability to dive to 6000 m. In form it is very similar to Cyana which is now some 15 years old. It will contain a personnel sphere in titanium but otherwise would seem to follow the design pattern formulated many years ago. Such submersibles have a diving endurance of some 8 - 12 hours in cramped conditions, and are very limited in the energy and payload they can carry and the variable buoyancy available. These factors limit their scientific usefulness to a marked degree.

There are those who believe that manned submersibles have reached the end of their development. However we do not incline to this view but rather believe that the present obvious shortcomings could be remedied, with suitable time and investment, to produce a new generation of autonomous vehicles with much improved performance and habitability. The scale of investment needed to adopt and engineer new technologies for a deep ocean submersible would justify European co-operation. This effort would include research on new hull materials (see section 7.8), energy storage (7.1), prime movers (7.2), buoyancy control, navigation (7.6) and other specialisations. If a vehicle were to be built, it could either be a higher performance one-dive vehicle, or multi-watch longer endurance vehicle, depending upon the engineering outcome of the design studies and the accompanying detailed scientific and investment needs.

We also believe that within the submersible sector the combination of an autonomous medium depth vehicle with an ROV, or small deep ocean manned submersible, should be explored as an alternative. This concept of a long endurance mother submarine carrying the basic 'work tool' is more flexible than the first system and would not require a direct mother vessel, and might find wider applications in depths from 1000 - 4000 m of interest to the oil industry. In such a system the mother submarine or submersible would include some of the design principles developed by IKL-Gabler and SSOS, and would be likely to employ a closed cycle fuel burning energy source.

In the context of manned submersible development, we would strongly recommend that the Comex-CNEXO Argyronête project is studied with a view to making a European technical and financial investment in the project so that the submarine can be used as a sea-going trials vessel. We believe it is well suited to be a platform on which new materials, energy sources, secondary cells, navigational equipment, processing, control gear etc. can be tested in a realistic environment.

8.8 Towed and suspended manned systems (27)

These systems are likely to be limited to depths of the order of 1000 - 2000 m and have limited and specialised commercial applications. Vehicles will be developed by commercial firms when required. We do not believe that there is any requirement for a European contribution to this sector.

9. RECOMMENDATIONS

This section concludes the report with a list of projects and specialist recommendations which we believe could be advanced by European co-operation and investment. The method of such co-operation, the level of investment required, the priorities of the different options and the degree of direct involvement by the Joint Research Centre would be a matter for further discussions and study in Phase 2 of this contract. The financing of operations, the logistics involved and the emergency support needed would also be considered in Phase 2.

Major vehicle projects recommended:

1. A 6000 m manned submersible, capable of remaining submerged for at least 4 days, with provision for shifts of crew and scientific observers, sophisticated navigation and data logging, and provision for extensive experimental equipment, including the use of manipulators and work tools.

2. A hybrid 'piggy back' submersible system consisting of a large mother submarine capable of diving to 1000 - 2000 m and carrying a smaller deep ocean vehicle capable of descending to 6000 m with a useful work payload.

3. An untethered remote operated vehicle with a depth capability of 6000 m and useful payload, including integrated navigation with intelligent control systems, 24 hour endurance and a high rate of data gathering with large volume storage.

4. A 6000 m remote operated vehicle, lowered in a 'garage' and capable of conducting sorties from the garage using an umbilical connection. Required to carry sophisticated work tools and video equipment.

Subsystem development recommended:

1. New materials, including carbon/graphite/kevlar fibre composites, metal-ceramic composites, etc., should be tested and developed for the construction of large pressure vessels and other components in manned and unmanned vehicles for deep ocean use.

2. The use of novel energy sources, particularly the closed cycle Stirling and diesel engine and their associated fuel systems, and certain secondary batteries, should be investigated. Comparative trials, and development and modifications should be carried out to evaluate the potential of each type of power source in realistic working conditions at sea.

3. Advanced computer and processing techniques, including the development of artificial intelligence, should be applied to the problem of controlling untethered remote operated vehicles and other systems to minimise the effects of low data rate and delay in signal transmission.

4. Development should be undertaken in advanced navigation systems for both manned and unmanned vehicles, integrating the optimum performance available from systems employing acoustic beacons, electro-magnetic logs, inertial navigation etc. Terrain following systems should be investigated for fast near-bottom surveys and the safe operation of manned and unmanned free vehicles.

5. Improved visualisation and acoustic imaging techniques, including pattern recognition schemes, should be developed for the better control of ROVs and work tools. Stereographic and holographic systems should be investigated.

6. Further development is needed, and test facilities are required, for umbilical cables capable of combining fibre optics with strain members and other conductors, with a maximum length of 10 km.

7. Test facilities should be developed for investigating the performance of materials, submersible components, subsystems and assemblies at depths down to 6000m, both in the laboratory and at sea, with the possibility of leaving materials or systems exposed for long periods.

8. The French submersible 'Argyronête' project should be examined with a view to supporting its development as an underwater test-bed for the sea trials of closed cycle engines and other energy sources, and the testing of other large components and subsystems in realistic operation conditions.

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APPENDIX 2 - BIBLIOGRAPHY

This bibliography contains those references used by the authors in the production of the report. Apart from the first group with a general application, they are arranged in the same order as the sections and sub-sections to which they refer. The bracketed numbers correspond to those shown in brackets after each section heading in the report.

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Four major vehicle projects were recommended in the report for consideration by Ispra and which would be options for a feasibility study in phase II of the programme. These were:

1. A 6000 m manned submersible, capable of remaining submerged for at least 4 days, with provision for shifts of crew and scientific observers, sophisticated navigation and data logging, and provision for extensive experimental equipment, including the use of manipulators and work tools.

2. A hybrid 'piggy back' submersible system consisting of a large mother submarine capable of diving to 1000-2000 m and carrying a smaller deep ocean vehicle capable of descending to 6000 m with a useful work payload.

3. An untethered remotely operated vehicle (UROV) with a depth capability of 6000 m and useful payload, including integrated navigation with 'intelligent' control systems, 24 hour endurance and a high rate of data gathering with large volume storage.

4. A 6000 m remotely operated vehicle (ROV), lowered in a 'garage', and capable of conducting sorties from the garage using an umbilical connection. Required to carry sophisticated work tools and video equipment.

This annex elaborates on these options and their use and also emphasises certain organisational features which we believe would be important for the successful development of any such option.

1. THE PROJECTS. TECHNICAL CONSIDERATIONS AND USE

Options 1 and 2. Manned submersibles.

In option 1 we are concerned with a 50-100 tonne submersible which can provide the endurance and comfort necessary to permit underwater sorties lasting 4 days or more. In a sense this is the next stage in underwater operations by submersible, where the 'bounce-dive' concept of Alvin, Cyana and SM97 is changed by the extended performance and payload which new power sources and hull materials would provide. The cost of present submersible operations is high, typically £10,000 - £15,000 per day, and is due in equal measure to the cost of operating the submersible and that of its dedicated handling vessel. However, the true cost of each hour actually spent carrying out underwater work is dependent on the vagaries of the weather for launch and recovery and the number of hours at the work site in an operational cycle. Although the development and capital cost of a submersible with extended endurance will be very much higher than the present generation of deep diving vehicles, it will allow for greater utilisation in a wider range of weather conditions and latitudes. By avoiding the need for launch and recovery, and by extending endurance, the number of useful hours of work on site in a given replenishment cycle will be increased. Furthermore, by doing away with a specialised handling vessel, a cost saving will be made. It is envisaged that such a submersible would operate in conjunction with a research vessel or deep sea trawler, unless the work site lay within, say, 200 miles of a base. If required, the ship could tow the submerged vehicle to the operating area and would be the source of stores and fuel as well as providing work facilities and for the exchange of crew. It could also undertake further offshore tasks while the submersible was operating.

During passage-making and when surveying it will be important for the submersible to make efficient use of the available stored energy between replenishment. This requires a clean hull form with low drag, and for optimum performance at great depths hull penetrations should also be kept to a minimum. Both these factors are best served by providing a portable tool and manipulator facility which is only mounted when required. This is also an advantage from the maintenance point of view since the ability to carry out in situ maintenance of externally mounted ancillary equipment will be very limited at sea. It is likely that the optimum solution is to provide a small ROV which can be transferred from the ship while the submersible is lying submerged a few metres beneath the surface, avoiding surface instability problems and wave action. This ROV concept would have other advantages, both in providing a very flexible work system at depth and a safety facility for the submersible. These aspects are discussed further in the section below on option 4.

Option 2 is a rather different approach involving the construction of a large autonomous mother submarine and a smaller deep-diving submersible which is transported to the site on the back of the larger vessel. Docking and undocking would be carried out at a depth of a few tens of metres, away from the effects of wave action. For operation in all oceanic weather conditions, possibly 2000 miles from base, it is clear that the mother submarine will have to be of a considerable displacement, and a figure of 1000-2000 tonnes has been mentioned by a naval consultant. Even with such a sizable parent submarine, the submersible is unlikely to exceed 20-30 tonnes in displacement due to the need to limit structural forces from wave action on passage. For such operations it seems unlikely, therefore, that the submersible component will be large enough to provide the performance and comfort necessary for extended use and its diving duration would be unlikely to exceed 24 hours. If, however, operations were limited to offshore tasks closer to land, then it is possible that the displacement of the parent submarine could be reduced. However, this places a severe limitation on the usefulness of the concept for a number of deep sea tasks. In option 2 the submarine is primarily acting as a specialised mother ship, with the main advantage that docking and undocking will take place away from the surface. The capital cost of such a vessel will be very high with high running and maintenance costs and the need for a crew trained to military standards.

Both manned submersible options (options 1 and 2) will require the same critical sub-system investigations and developments during the design study stage. The main difference will be in detail emphasis and in the size of hull and energy sources needed. These sub-system developments include:

- Energy sources and storage
- Material study and pressure vessel design
- Navigation
- Buoyancy control
- Manipulation and tooling facilities.

These topics are covered in some detail in section 7 of the report. Apart from this particular requirement for these sub-system developments, the work would result in valuable technological gains for the European offshore industry.

An analysis has been carried out to determine the degree of use of the four options amongst the potential users listed in section 5 of the report. To a first approximation, both manned submersible options serve the same potential users and these cover 15 out of the 19 subjects listed. Main users are seen to be:

Offshore oil and gas industry

- In exploration and production
- Repair and maintenance of structures, pipelines, etc.
- Non-destructive testing

Military

- Salvage of crashed aircraft, instruments and weapons
- Submarine rescue

Research and monitoring activities concerned with the deep sea disposal of radioactive waste
Biological research
Geophysical and geological investigations and research
Geochemical investigations and research.

The last two subjects would cover commercial mining interests as well as more basic research. A users panel would need to involve representatives from the offshore hydrocarbon industry, military interests, radioactive waste disposal interests, offshore mining and the marine research field.

Option 3. Untethered remotely operated vehicle (UROV)

This option is concerned with the design study and construction of a free-swimming unmanned vehicle able to carry out both pre-programmed and 'intelligent' surveys at depths down to 6000 m with an endurance of 24 hours. Design features of importance would include the ability to accurately navigate along survey lines say 100 m apart within a frame of a few kilometres, and also to carry out longer range reconnaissance work under the guidance of an intelligent control system. It is envisaged that the sensor suite would be varied according to the task undertaken, but would include a wide range of navigational, acoustic, optical and geophysical instruments. It is unlikely that sufficient energy could be provided at the required survey speeds of 4-6 knots by batteries alone so there would need to be a primary energy source and recharging system fitted. Operations would not need to take place from a specialised vessel, although adequate articulated craneage would be required to handle a vehicle weighing, say, 5 tonnes in air. Although operational navigation would be provided by the vehicle's own instrumentation, supplemented by a long base line system when required, it might be necessary to provide a short base line tracking system on the surface vessel, mainly for recovery.

A number of the major sub-systems which would have to be developed would be similar to those for options 1 and 2, and would again have a more general application in European underwater technology in the commercial, military and marine research fields. These would include:

Energy storage and recharging systems
Pressure vessel materials and design
Hybrid navigation, integrating a number of modes
Buoyancy materials and control
Intelligent control system
Acoustic telemetry

High capacity data storage
Sensor suites (navigational, acoustic and optical)

Technical aspects relating to these are discussed in section 7 of the report.

The analysis of user's needs suggests that the range of possible users for such a vehicle may not be as great as in the manned submersible options. This is largely because the vehicle is seen as a remote survey instrument with no significant ability to carry out the type of on-site work tasks which a manned submersible (or cable-connected vehicle - ROV) could undertake with real-time vision coupled to a manipulator and tool facility. However, there is no doubt that the development of such a vehicle would be valuable to a number of users, and in many ways would complement that undertaken by the offshore industry, particularly in their emphasis on ROV development. Once developed and proven, it would provide a very efficient and cost-effective way of carrying out precise surveys and reconnaissance work. The main users are likely to be:

Offshore oil and gas industry
- Deep site surveys
- Deep pipeline routeing surveys
- Salvage and 'litter' surveys

Military
- Location of crashed aircraft, instruments and weapons

Research and monitoring activities concerned with the deep sea disposal of radioactive waste

Geophysical and geological surveys.

The last named would include both commercial and research interest in nodule fields and metalliferous deposits as well as more basic sedimentary and tectonic studies. Unmanned free-swimming vehicles have a particular application in such research since they offer the prospect of conducting surveys of a given area of ocean floor at relatively high speed and with much more precise track control than that provided by a deep-towed system. Such a technique would enable maps to be produced of the morphology of the sea bed, of sedimentary facies and structure comparable to that on land. Areas of resource potential, such as concentrations of manganese nodules or polymetallic sulphide ore bodies, could be mapped in considerable detail.

Option 4. Remotely operated vehicle (ROV)

This option is concerned with the development of an unmanned cable-controlled vehicle, or ROV, capable of operating down to 6000 m in the ocean. Operations would take place from a 'garage' suspended by cable from a ship able to provide the necessary winching facilities and handling gear. The vehicle would be connected to the garage by a neutrally buoyant umbilical cable allowing a radius of action of a few hundred metres. Important design features would include dextrous manipulation and tooling facilities coupled to a wide bandwidth video system for precise control. The ship would be fitted with a short base-line position system capable of giving the ROV position to 0.1% of the depth. The ability to reoccupy a site would be enhanced by the use of the global positioning satellite navigation network.

Certain major sub-system developments would need to be undertaken including:

Cable and umbilical design, including the use of fibre optic cores in long strain-bearing cables

High resolution video system and signal transmission over long path lengths

Manipulation and tooling facilities

Improved short base-line positioning system

Again, many technical aspects of these subjects are covered in section 7 of the report. It could be said that the development of the major sub-systems required for deep ROV operation (below 2000 m) are likely to be undertaken by the offshore industry when the economic situations demands. However, there are certain developments which will require the use of major experimental test facilities etc. which would benefit from a central European programme and funding. This is particularly true of the problem of providing high resolution video images for the control of ROVs at great depth. To provide the necessary low cable attenuation and high bandwidth (up to 10^8 bits/sec) it will be necessary to include fibre-optic cores in the strain cable which will be 8000-10,000 m long. The problems which this raises, both in terms of quality control of the fibres in manufacture and their successful integration in a strain cable, are very considerable, and it will be necessary to include long term fatigue trials of prototype lengths.

An analysis of users' needs indicates that the development of such a vehicle, and its attendant technology, would be of value to a wide range of users and tasks. Major users would include:

Offshore oil and gas industry

- Exploration and production
- Pipelaying surveying and inspection
- Repair and maintenance of structures, pipelines etc.
- Non-destructive testing

Military

- Location and salvage of crashed aircraft, instruments and weapons
- Assistance in submarine rescue

Monitoring and servicing activities concerned with the deep sea disposal of radioactive waste

Biological research (servicing benthic stations)

Geophysical and geological investigations and research

Geochemical investigations and research

The last two subjects would include commercial mining interests as well as more basic research. A users panel would need to include representatives from this wide range of activities.

An additional activity is related to work in support of option 1, a manned submersible operating in the neighbourhood of a surface ship which acts as its base. As explained earlier, there would be certain advantages if such a submersible could work in conjunction with, or carry, a small ROV capable of operating at 6000 m. It is conceivable that the ROV considered in option 4 could have this dual role. It could be both a 'stand-alone' facility and, when required, it could work in conjunction with such a submersible. In the latter case, either in its normal mode with cable and garage, when it could provide a surface-controlled facility to complement the work of the submersible, or as an auxiliary manipulation and tool facility mounted on the submersible. When it was required on the submersible the latter could lie submerged a few metres below the surface and release a buoyed umbilical cable which would be lifted aboard the ship and attached to the ROV vehicle. The vehicle would be lifted into the water, released, and then be manoeuvred by the submersible onto a cradle behind the fin. Since most ROV offshore activities require a back-up vehicle in case of breakdown, it is likely that a second vehicle would be available for use. This concept of a deep-diving submersible working with its own ROV is likely to prove a powerful one; the submersible crew, including specialists, would be at the work site with direct vision which can be supplemented by high resolution video on the ROV aided by short cable signal transmission. The ROV would not be limited by the inertial forces which restrict the manoeuvrability of the more massive submersible so that it would provide the latter with a dextrous tooling facility for a range of site tasks. The ROV also provides the submersible with a 'front-line' safety feature which the crew can use in case of emergency to aid recovery.

The most valuable rescue aid for such extreme depths far from land will be a second ROV held on the surface ship which can be used to provide emergency power or attach a lifting warp.

2. GENERAL COMMENTS ON THE ORGANISATION

It is understood that one or more of the preceding options may be the subject of a feasibility study in Phase 2 of this contract. After this second phase has been completed, and if a decision is taken to go forward to a design study, then it will be necessary to set up an organisational structure which will include financial, managerial and technical components. At this present stage we do not wish to suggest the detailed form this structure might take but would like to make one or two general comments.

The successful direction and management of a sophisticated technical project involving a number of countries and many centres of design and manufacture is a task of considerable magnitude. There will be pressures brought to bear on management from a number of sources, particularly of a political, industrial and financial nature, apart from those of a direct technical origin based on the need to reconcile the requirements of users with the many engineering limitations posed by such a new technology. In order to ensure that technical progress is made in a way which correctly reflects users' needs, and allows engineers a reasonable flexibility in meeting these needs without undue external interference, certain lines of communication and levels of responsibility need to be clearly defined. In this context we believe that a Technical Director is required who would be solely responsible to the national representatives for the successful engineering development and completion of such a project within the agreed cost and delivery constraints. Daily administration would be carried out by a management team who would be served by advisory panels of users and technical consultants. In addition contractors would be appointed to carry out the necessary project and sub-system design studies and development. The Director would need to have very considerable experience in the field of underwater technology and in directing innovative engineering projects of a sophisticated nature. He would need to understand users requirements in detail, to identify areas of conflict and to seek out the most cost-effective solutions in consultation with his technical advisors. In addition, as the design studies progress, certain technical limitations will become apparent and it will be the Director's responsibility to expedite any changes in the direction of the engineering development to circumvent these limitations in the optimum way. Successful completion of the project will owe as much to this ability to maintain the best technical balance and direction as it will to the innovative ability of the engineering teams involved.

We believe it is important that users are involved from an early stage. In a very real sense the project should be 'user-led'. This involvement ensures that technical teams start, continue and complete their work within the constraints of well-defined needs. It should also facilitate close interaction between users and engineers when changes in direction may be required at short notice. Morale on both sides benefits from such a liaison, and not least, public accountability requires that money is directed in this way to help solve clearly stated needs.

There are several precedents for international science and engineering projects, where committees and advisory groups representing users work with an executive agency, a funding agency, and contractors, to develop and manage a system. Examples include the Deep Sea Drilling Project (DSDP), Geochemical Ocean Sections Programme (GEOSECS), European satellites such as the oceanographic satellite ERS-1, or the collaborative research on radioactive waste disposal in the sea bed. We envisage that comparison with the structure of some of these projects would help to suggest ways of administering the proposed remote handling options, both in the development and operational phases.

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