National Biofilms Innovation Centre

Microbe-Metal Interactions

WORKSHOP REPORT

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Contents

NBIC WORKSHOP

Executive Summary

This workshop brought together key complementary academic expertise and thought-leadership from industry in biofilms, contamination of metal surfaces and biocorrosion processes across the life and physical sciences and engineering domains within NBIC, CBE and internationally in order to identify the key knowledge gaps and research challenges for future projects and research collaboration.

The problems associated with Microbe-Metal interactions impact multiple industries such as chemical processing, nuclear power generation, onshore and offshore oil and gas, water treatment, sewage handling and treatment, highway maintenance, aviation, metal working, marine and shipping. The economic impact is significant (estimated for the USA as 3.2% of GDP). The challenge is still largely intractable and there remain fundamental scientific challenges in its prediction, early detection, prevention and control.

Invited workshop participants shared unmet needs and the current state of knowledge of interactions between complex microbial communities and metals, with a focus on the challenge of microbially influenced corrosion (MIC). The primary objective was to identify the key knowledge gaps and research challenges for future projects and research collaboration.

We thank the Biotechnology and Biological Sciences Research Council (BBSRC) for funding the costs of the meeting through a US Partnering Award. Further details here. More details here.

Key challenges considered were:

1) Achieving improved risk assessment, prediction, and modelling (e.g. being able to predict and understand where, when, and why does biofilm form in a particular system).

2) The elucidation of coupled microbial metabolisms and potential novel bio-markers remains a key need. Improved understanding of the interplay between microbes and the surface may lead to identifying key markers.

3) Creating improved methods for detection of biofilms and monitoring of systems (e.g. deployable, accurate, sensitive biofilm/ corrosion sensors).

4) Identifying improved concepts to prevent biofilm formation (e.g. new materials/ surfaces/ coatings to disrupt biofilm life-cycle dynamics).

The key areas of emerging science felt to be critical by attendees were:

1) Mechanisms and models of the interactions of the microbe-metal. In all fields of biofilm study including MIC there is a need for improved models that can truly recreate the real-world situation or model it in such a way that accurate predictions can be made and interventions can be realistically assessed.

2) Surface science. Technologies for understanding of the metal surface and the ability to measure, interrogate, visualise and modify it are key tools.

3) Sensor technologies. Groups discussed the need for early detection and monitoring of biofilm formation and MIC occurrence. Sensors are a key tool to achieve this but have to be deployable, accurate and sensitive if they are to be of use to industry.

4) Materials/coatings. Approaches that enhance a surfaces ability to prevent biofilm formation are critical for addressing unmet needs. These could be improved surface designs, treatments and/or coatings.

There was a clear consensus that a consortium with multiple industry and academic partners was needed to move ahead impact on the challenges identified. From the information gathered during this workshop a comprehensive picture was built of challenges faced by the industry as well as suggestions for how these challenges can be addressed. Many of these are either training based or exist in the precompetitive space, the simplest solution is a consortia approach consisting of NBIC, CBE, industry and academic partners. This consortium can create and run a series of training and engagement events/ materials for front line staff who are non-microbiologists as well as developing the identified areas of research and innovation into a series of joint projects including seeking and applying for potential sources of funding.

Background: Biofilms in Context

Microbial biofilms and communities collectively represent the largest biomass and activity centre on the planet playing a major role in the biology of the environment both natural and engineered.

Compared to unbound bacteria of the same species, biofilms are typically resilient to biocides and so can be challenging to control. They can present risks to human and animal health, introduce food safety problems, disrupt production from oil and gas wells and contaminate potable water supplies.

They can also be useful. Waste-water treatment processes make extensive use of biofilms, they can increase the bioavailability of nutrients in the soil and seal cracks in borehole casings. Our estimate is that biofilms impact about $5,000bn of economic activity, approximately twice the GDP of the UK[1].

Background: National Biofilms Innovation Centre (NBIC)

NBIC was formed in December 2017 as an Innovation Knowledge Centre (IKC) funded by BBSRC, Innovate UK and the Hartree Centre.

NBIC has the mission of harnessing the UK's Industrial and Academic strength in biofilms.

NBIC aims to be the recognised UK hub for accessing biofilm expertise, capability, science and innovation capacity. It has been tasked with catalysing the growth in the UK's scientific, technological and industrial expertise in biofilms with the goal of delivering:

- World class science and scientists,
- Breakthrough innovations,
- Economic and societal value.

NBIC is working to create a network and community of researchers and industrial/ commercial partners across the UK and internationally to progress all these elements.

This workshop has arisen from an international workshop award (UKRI BBSRC) to develop a partnership between the USA's Centre for Biofilm Engineering (CBE) at Montana State University and the UK's National Biofilm Innovation Centre (NBIC). This workshop and others held by NBIC (Biofilm Detection, 2018 and Biofilm Engineering, 2019) are one key dimension in achieving these goals and are intended to create a forum whereby academic experts and industrial practitioners can meet to explore solving unmet needs.

In trying to both tackle and utilise biofilms the industrial and research communities have defined 4 key interventional strategies:

- Prevent: To limit or prevent the early stage microbial adhesion and colonisation events at surfaces. This could employ the use of advanced techniques to create the knowledge-based design of next-generation surfaces.
- Detect: To deliver a step change in the ability to detect biofilms directly, in situ, at the point-of-use in field-based contexts and close-to-patient care through accurate and quantitative biofilm detection and metrology across multiple scales.
- Manage: To destroy, remove or control established biofilms by understanding and exploiting their life cycle dynamics and development across a range of environments and levels of complexity. Also, to accelerate the development of successful treatments, which target the biofilm life cycle-dynamics and intricate structure, through the creation and use of biofilm models resembling real environments.
- Engineer: To harness the benefits of complex microbial consortia from knowledge of their composition, function, ecology and evolution. This exploits understanding at the interface with engineering and process applications. It includes improving engineered platforms and solutions e.g. wastewater, biotechnology, resource recovery from wastewater, microbial fuel cells, aerobic and anaerobic biorefinery.

Background: Center for Biofilm Engineering (CBE), Montana State University

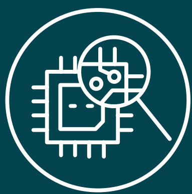
Montana State University's Center for Biofilm Engineering has been a world leader in biofilm research for 30 years. A prestigious 11-year National Science Foundation Engineering Research Center grant awarded in 1990 paved the way for the CBE's influence in the emerging field of biofilm research.

The Center's three-fold emphasis in research, education, and industry continues to produce results and exciting opportunities for students, staff, and faculty - as well as industrial partners.

The mission of the Center for Biofilm Engineering is to advance the frontiers of health, energy, industry, and the environment through biofilm research, education, and outreach.

PREVENT

Knowledge-based design of surfaces, interfaces and materials



DETECT

Innovative sensing, tracking and diagnostic technologies

MANAGE

Kill, remove or control established biofilms from exploiting their life cycle dynamics

ENGINEER

Control and direct complex microbial communities in process applications

Addressing global challenges in biofilms and biocorrosion

The main objective of this workshop was to bring together key complementary academic expertise and thought-leadership in biofilms, contamination of metal surfaces and biocorrosion processes across the life and physical sciences and engineering domains within NBIC, CBE and internationally in order to identify the key knowledge gaps and research challenges for future projects and research collaboration.

MICROBIALLY INFLUENCED CORROSION

Although many man-made objects and structures are made from inorganic and/or inert materials such as metals, concrete and polymers they are subject to corrosion arising from the activities of microorganisms including biofilms. For example, some bacteria reduce sulphate to hydrogen sulphide which can cause stress cracking. Other Acidithiobacillus bacteria produce sulfuric acid which can damage materials, and Ferrobacillus ferrooxidans directly oxidizes iron to iron oxides and iron hydroxides. This microbiological reaction can take place in sea and fresh water as well as soils, and with pH 4~9 and temperature 10°C~50°C.

Many industries are affected by microbially influenced corrosion that include[2]:

- Chemical processing industries: stainless steel tanks, pipelines and flanged joints, particularly in welded areas after hydrotesting with natural river or well waters;
- Nuclear power generation: carbon and stainless-steel piping and tanks; copper-nickel, stainless, brass and aluminium bronze cooling water pipes and tubes, especially during construction, hydrotest, and outage periods;
- Onshore and offshore oil and gas industries: mothballed and waterflood systems; oil and gas handling systems, particularly in those environments soured by sulphate reducing bacteria (SRB)- produced sulphides;
- Underground pipeline industry: water-saturated clay-type soils of near-neutral pH with decaying organic matter and a source of sulphate reducing bacteria;
- Water treatment industry: heat exchangers and piping;
- Sewage handling and treatment industry: concrete and reinforced concrete structures;
- Highway maintenance industry: culvert piping;
- Aviation industry: aluminium integral wing tanks and fuel storage tanks;
- Metal working industry: increased wear from breakdown of machining oils and emulsions;
- Marine and shipping industry: accelerated damage to ships and barges.

The corrosion mechanism takes place as a consequence of biofilms. Structures can be complex with aerobic and anaerobic regions, and the corrosion mechanisms include chemical and electrochemical effects. In addition to direct corrosive impact, biofilms can lead to the formation of inorganic scales[3]. Methods of prevention include mechanical cleaning, chemical treatment and drainage/ dry storage. These approaches are not always easy or practical to execute.

The question arises as to the economic significance of corrosion. Data is available on the total impact of corrosion (of which MIC will only be a proportion) in the United States of America, which was $276bn in 1998 – equivalent to 3.2% of US GDP[4]. These are the direct costs of the corrosion, not the subsequent indirect economic costs.

If expenditure on corrosion remains an unchanged proportion of the US economy, this is equivalent to $564bn in 2016[5]. This figure includes all types of corrosion. The proportion attributed to biofilms is at least 20%[6]. This leads to a figure of $113bn.

The figure for the UK can be estimated assuming that microbial corrosion accounts for a similar proportion of GDP in the UK. The result is £10.7bn for 2016[7]. The global figure can be estimated as $475bn for 2015 by applying the same proportion of GDP[8].

In particular, the challenge of pitting corrosion is still largely intractable and there remain fundamental scientific challenges in its prediction, early detection, prevention and control of corrosion caused by microbial communities on metal surfaces.

The challenges and costs presented by corrosion are leading to investigations of ways to reduce the current and future costs of corrosion. Examples of such activities include new treatment regimes to remove biofilms, new materials that are not vulnerable to corrosion and investment in coatings that can protect surfaces.

OIL AND GAS PRODUCTION

The high temperatures and pressures, high salinity and abundant presence of hydrocarbons would appear to make oil and gas wells a hostile place for microorganisms, yet biological activity is significant in the oil and gas sector. It can induce unwanted corrosion, produce unwanted hydrogen sulphide which sours the hydrocarbons and also lead to plugging of flow channels. They can also assist oil and gas extraction. For example, deliberate injection of sugar-based materials to support microorganisms has been found to increase oil production[9]. They have also been found to seal microscopic fissures in the casings of wells through microbially induced calcite precipitation. The integrity of wells is a point of considerable interest in the industry and also in the debate about fracking technology and the risks to ground water. The ability to remotely monitor and prevent and selectively enhance biological activity underground is therefore of considerable importance to the oil and gas exploration and production industry.

Control strategies recognise that complete sterilisation is not an achievable goal but the use of biocides may reduce the numbers of microorganisms to levels that can be tolerated. The quantities of treated water required can be vast - for example, Saudi Aramco's Qurayyah Seawater Treatment Plant has a daily capacity of 14 million barrels (2,200,000m3) of treated seawater for oil production throughout the kingdom. Biocide resistance is increasing the quantities needed - for example, in oilfield operations, the initial dosage of tetrakis hydroxymethyl phosphonium sulphate (THPS), a green biocide popularly used in many oilfield operations, may be 50 or 100 ppm (w/w). Years later, 500 or even 1,000 ppm would be needed due to biocide resistance[10]. A high biocide dosage is not only expensive, but also causing environmental concerns when it is discharged. This is leading to the need for control measures that do not require biocides use at all[11].

The remote location had also made monitoring of biological activity difficult although advances in molecular biology is leading to new methods for detection and measurement. This is also leading into enhanced insight into the microbiological mechanisms of corrosion and souring. One control strategy to reduce souring of a reservoir is to inject calcium nitrate to stimulate nitrate-reducing bacteria which outcompete the sulphate- reducing bacteria for nutrients, thereby reducing the formation of hydrogen sulphide.

Biofilms are also important to the treatment of oil contaminated wastes produced by the sector, particularly hydrocarbon-impacted soil and drilling waste. Bioremediation can be stimulated by treatment with a combination of nutrients and cultured microbes tailored specifically to the hydrocarbon composition of the waste[11].

Microbially enhanced oil recovery is an established method to increase the recovery of oil from oil reservoirs. The aim is to use microorganisms to reduce viscosity or reduce surface tension to enable greater recovery or hydrocarbons. The benefits need to be balanced against the disadvantages such as cost and increased corrosion Conventional primary extraction recovers 5-15% of the total reservoir, secondary methods increase this to 20-60% but microbially enhanced oil recovery takes this further to 35-75%.

Use of the method is growing rapidly with annual growth rates forecasts of up to 20%. The scale of the sector is expected to be $400bn by 2019. There are extensive field trials to develop the method, but rigorous controlled experiments are lacking. The science of microbial action in enhanced oil recovery is complex, involving the interplay for various chemical, physical and biological systems. The application of microbial methods is not completely understood so it is not universally successful. Challenges remain in the prediction of microbial action, its impact and how to beneficially harness it.

Microbe-Metal Interactions Workshop

1.1 SETTING AND AIMS

The workshop was held in London on 22 November 2019.

A group of interdisciplinary experts attended the workshop in order to develop a shared understanding of the unmet needs and current state of knowledge of interactions between complex microbial communities and metals, with a focus on the challenge of microbially influenced corrosion (MIC), and to identify projects and actionable ways forward.

This aim was to address the following **enduring challenges** for those working in the field:

1) Achieving Improved risk assessment, prediction, and modelling (e.g. being able to predict and understand where, when, and why does biofilm form in a particular system).

2) The elucidation of coupled microbial metabolisms and potential novel bio-markers remains a key need. Improved understanding of the interplay between microbes and the surface may lead to identifying key markers.

3) Creating improved methods for detection of biofilms and monitoring of systems (e.g. deployable, accurate, sensitive biofilm/ corrosion sensors).

4) Identifying improved concepts to prevent biofilm formation (e.g. new materials/ surfaces/ coatings to disrupt biofilm life-cycle dynamics).

The intended outputs of the day were:

- Confirming the key challenges in the area that can be addressed with emerging technologies (the enduring challenges 1-4 being used as a start point).
- Development of both specific projects as well as identifying major strategic collaborative funding initiatives.
- Propose joint projects (PhD or other), student internships and postdoctoral exchanges with consortial funding.

The workshop committee[12] invited industry and academic experts from the Oil and Gas sector and relevant fields of research respectively. Thirty-nine delegates attended the workshop, comprising of fifteen from industry representing twelve companies, and twenty four from research institutions and UKRI; representing thirteen organisations.

To provide inputs to the meeting, all delegates were asked to consider five questions relating to microbially influenced corrosion (MIC) by completing an online form (Appendix 1). Non-attributable comments from the form were used during the workshop and subsequent reporting.

1) What do you see as the key challenges in respect of your sector or field? For example, is it:
   - knowing where, when, and why biofilms form?
   - how to elucidate coupled microbial metabolisms and potential novel bio-markers?
   - how to Improve detection and monitoring?
   - how to prevent biofilm formation?
   - something else?
2) What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?
3) What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?
4) What cost and timescale might this be?
5) Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?

Following a welcome and introduction by Dr Mark Richardson, Prof. Matthew Fields and Prof Jeremy Webb there were two presentations. One by Dr Jaspreet Mand (Senior Research Engineer, ExxonMobil) entitled 'Management of microbially influenced corrosion (MIC) in the oil and gas industry' and one by Professor Joseph Suflita (University of Oklahoma) entitled 'Can we ever really measure the number and activity of active microbes involved in MIC'.

1.2 WORKSHOP OUTPUTS

The delegates then joined cross industry/academic syndicate sessions on defining the key challenges and defining the research questions before identifying the main priorities and next steps. The NBIC team collected all the output (Appendix 2) and along with the pre-submissions (Appendix 1) these formed the basis of this summary report.

1.3 DISCUSSION

Before and during the workshop, the delegates identified the key challenges of microbially influenced corrosion both from an industry and academic perspective. Individual delegate output is provided in Appendix 1, with the output from the breakout groups in Appendix 2. The main themes that emerged from these discussions across all groups are:

1. What are the key challenges?

- Being able to model (laboratory, small scale, in silico) where and when a biofilm may form and corrosion could occur in a system.
- The complexity of the corrosion process and the interplay between species, surface and the various mechanisms make this a challenging area to unravel. Being able to link the microbiology to the chemistry and electrochemistry that is occurring in vivo.
- Remote/online detection and monitoring of biofilm formation and early warning if MIC is taking place and being able to differentiate between chemical and microbially influenced corrosion.
- Prevention of biofilms is the ideal situation for example, via system and materials/surface design **but** if not then the complete removal of biofilms through non-hazardous mechanisms is required.
- Standardisation of methods/models to assess corrosion/ the causative biofilm composition in various environments. In order that data can be compared and solutions can be better assessed these models have to be realistic i.e. corrosive biofilms not just biofilms.
- Providing tools, methods and interventions that are suitable for the end user. These have to be fit for purpose in a real-world environment e.g. remote locations, difficult to access. If they are prevention approaches then they preferentially need to be capable of being retrofitted.
- Understanding the initiation times between bacterial contamination, biofilm formation to active corrosion.

2. What is the emerging science and technologies that could address these challenges?

All groups felt that to exploit the leading-edge science then the key need was for a Joined up interdisciplinary approach and an industry wide collaborative effort. These problems touch multiple sectors and settings and the science and the end users need to be in communication in order to share the challenges described above and progress/ translate solutions to practical reality. The key areas of emerging science that were felt to be critical were:

- Mechanisms and models of the interactions of the microbe-metal.
- In all fields of biofilm study including MIC there is a need for improved models that can truly recreate the real-world situation or model it in such a way that accurate predictions can be made and interventions can be realistically assessed. Such models should be standardised across workers and if one model cannot achieve all that is needed then models at different scale that can relate one to another should be considered. These models should also allow more detailed study of the mechanisms of corrosion and the interplay between the microbes and the surfaces/ system.
- Surface science.
- Technologies for understanding of the surface and the ability to measure, visualise and modify it are key tools.
- Sensor technologies.
- Groups discussed the need for early detection and monitoring of biofilm formation and MIC occurrence. Sensors become a key tool achieve this and have to be deployable, accurate and sensitive. These could target microbial markers or chemical/ electrochemical events shown to be predictive in model and real-world systems based on knowledge of the mechanisms of corrosion and microbes involved. Sensor technology is rapidly developing and solutions to these needs could be being processed in multiple application fields so a wide awareness and outlook is needed.

- Materials/ coatings.
- Approaches that enhance a surfaces ability to prevent biofilm formation are critical for addressing unmet needs. These could be improved surface designs, treatments and coatings. This involves metallurgy, the deployment of surface science tools and the creation of unique coatings and surface treatments. A Key plea is the need for the ability where possible to be able to retrofit solutions to existing assets e.g. pipelines.

Other technologies that were considered in discussions included:

- The use of metagenomics to study the microbiome of the setting in order to get an accurate picture of the full microbial population.
- Biocides for controlling established biofilms (regulatory constraints exist in selecting these and developing new interventions).
- Intelligent Pigs. Often used for cleaning, pigs that can sense and measure parameters already exist and so these could be broadened in their capability in order to deploy MIC sensing and other approaches.

3. How should we organise ourselves to address these challenges?

There was a consensus that a consortium with multiple industry and academic partners was needed to move ahead addressing the challenges identified. This could develop and seek to gain funding for interdisciplinary, organised projects under a programme of translational research. The consortium needs to be inclusive so for example ensuring that those involved with offshore wind structures and the water industry are also included when addressing these challenges.

Other key points that came out of the breakout discussions:

- The need for a platform to bring together a 'community, a forum, a village' to facilitate collaboration across multiple disciplines and organisations.
- Effective communication with end-users about what microbially influenced corrosion is (and isn't).
- Developing training and education programmes on corrosion.

1.4 CONCLUSIONS AND NEXT STEPS

From the information gathered during this workshop we have built a comprehensive picture of challenges faced by the industry as well as suggestions for how these challenges can be addressed. As most of the challenges faced by the industry are either training based or exist in the precompetitive space, the simplest solution is the suggested consortia approach consisting of NBIC, CBE, industry and academic partners. This consortium can create and run a series of training and engagement events/materials for front line staff who are non-microbiologists as well as developing the identified areas of research and innovation into a series of joint projects including identifying and applying for potential sources of funding.

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11) *Microbes - oilfield enemies or allies?* **Augustinovic, Zdenko and al, et.** 2, 2012, Oilfield Review, Vol.

12) Prof. Miguel Cámara (NBIC, University of Nottingham) Prof. Matthew Fields (CBE), Ms Kristen Griffin (CBE), Prof. Ian Head (Newcastle University), Dr Mark Richardson (NBIC), Dr Jo Slater-Jefferies (NBIC), Prof Jeremy Webb (NBIC, University of Southampton).

Appendix 1: Pre-workshop questions relating to microbially influenced corrosion (MIC)

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
In my view there is a distinct lack of standardisation in the methods to detect, evaluate and mitigate the risk of MIC to pipeline integrity.	It appears that one of the most complex issues regarding MIC is the sheer number of different mechanisms and different microbes that can arise. I think that recent advances in cloud-based computing could be leveraged to apply data science solutions such as machine learning to cut through the complexity to identify common trends that can then be addressed through traditional corrosion science methods.	To address this issue would certainly require a multicentre collaborative approach. The main reason for this is the diverse range of expertise required to address the problem. It covers, microbiology, computer/ data science electrochemistry and engineering.	To have a meaningful impact and deliver a tool or tools that industry can use, I think you would need in the region of 5 years.	Not right now, but I will think on it.
Something else... The key challenges are twofold. First, biologists often underestimate the complexity of corrosion. Second, corrosion scientists and engineers often underestimate the complexity of biology. Accordingly, a full and accurate 4D finite element model of biocorrosion is fraught with difficulties, which I believe are insurmountable. However, modelling is essential to gain insight, and much can be gained by attempting to understand the dynamic interaction between biology and a corroding substrate.	Certainly genomics, and showing how the corrosion process introduces a selection pressure on the developing and maturing biofilms. With regard to corrosion, there is still much to be had from electochemical noise monitoring, though when I last attended my last conference on MIC (a decade ago), I was saddened to see that nothing had moved on in the twenty years since I first engaged with the field. Since that time, genomics has, of course, made a big impact in all aspects of microbiology and will continue to assist in uncovering the uncertainties within MIC.	Initially, the ability to replicate in the laboratory the MIC corrosion mechanisms. If these cannot be physically modeled, then the physical system is not understood, and therefore a 4D simulator cannot be underpinned with the required physiochemical and biological principles.	Crumbs... I've been in the field for thirty years, and the answer is always 'within the next decade'. As I said, I think modelling MIC [under all circumstances] is insurmountable, but we shouldn't stop trying. Will this be a field that requires AI, neural networks and quantum computing to model? Perhaps, and that would be fun!	The unknown unknowns. I don't know!

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
– Knowing where and when biofilms form through simulation. – How to improve online detection and monitoring - biofilms and MIC?		Collaboration with industry	2-3 years	Distinguish biofilm from other films or deposits e.g. iron sulfide film, mineral deposits, scale deposits.
Knowing where biofilm formation initiate is definitely important. For example, are there locations on the metallic alloy where biofilms prefer to attach and initiate biofilm formations? Our past experience indicate that metallurgy plays a major role in initiation, development and growth of localized pits on the surface. For example, we can relate these locations to the metallurgical history of the alloy. This means initially these areas are the locations give rise the anodic reactions where Fe+2 ions are concentrated. Will the microorganisms by virtue of being in need of iron be also localized and initiate biofilms at these locations?	High spatial and spectral microscopy including surface sensitivity and cross section analysis aided by emerging focused ion beam technologies will be very important. High spatial resolution electrochemical analysis based on AFM technologies, surface sensitive integrated Auger Nanoprobe and high spatial resolution TEM analysis as well as high-end Raman spectrometry will be highly desirable.	In my opinion basic research is lacking on these subject. However, we should always keep foot in real world keep close collaboration with the applied side of the research that includes problems encountered in the private sector. However, we should not be afraid to spent some money to study hypothesis based fundamental research which has implications in future applications such as described in (1) above.	Difficult question. For my group a 5 year intensive research in collaboration with other groups with expertise in microbiology, electrochemisty and metabolomics with a 5 million dollar direct cost will make a serious contribution to the field provided that we have access to required analytical tools described in item (4).	I would like answer the question based on our experience that led to the hypothesis that the locations of pitting corrosion is determined by the metallurgical history of the alloys and the rate of degradation of alloys is determined by the presence and activity of the microorganisms on the surface.
From our point of I view it is how to get an early warning if MIC will take place. That means that it is necessary to better handle detection and monitoring. A way to solve that could be to look into microbial metabolites.	Metabolomics (may be coupled with metagenomics)	Applied research in collaboration with the industry. Microbiologists and electrochemists need to work together.	3-4 years.	
How to improve detection and monitoring to get an early warning if MIC take place	Metabolomics (Metagenomics)	Applied research in collaboration with industry. Microbiologists and electro chemists should work together	3-4 years	

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Knowing where and when biofilms forms is useful for the purpose of developing effective mitigation, but how biofilms form is somewhat immaterial as long as it can be effectively removed with use of mechanical or chemical means. When a biofilm is detected then monitoring and mitigation are important. Any technologies that can prevent, or completely remove, biofilms in a non-hazardous manner will be of interest.	We have come across several companies pitching ultrasonic and ultraviolet as eco-friendly techniques for prevention of biofilms. However, these technologies lack the scientific vigour and demonstrable applications to be confident of deployment on active warships. There are numerous biocidal/bleaching techniques available in the market which are likely to be phased out due to their hazardous effects on the environment. Coatings doped with natural anti-microbial materials such as silver / copper that can have controlled release to be effective against biofilms and non-hazardous effect on environment can also be of interest.	We will be interested in applied collaborative research that results in development of demonstrable products and applications to prevent/remove biofilms form seawater systems.	Typical ICASE funding and 3 years timescale	NA
How to detect and monitor microbial (presence and) activity in oil and gas production pipelines and equipment. One possibility to do so could be to elucidate coupled microbial metabolisms and potential novel bio-markers	Study metabolomics and metagenomics	I think that it is important to establish a collaboration within oil and gas industry and build a database of field samples	Timeline could be 3-4 years Cost should be discussed during the workshop	

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
I think it inevitable that microbes will colonize surfaces (coated or not) and will have the potential to accelerate corrosion problems. I think it is important to distinguish between anaerobic corrosion processes and simple rusting under aerobic conditions. I think it is also important to quantitatively assess corrosion in high organic environments vs. low organic ecosystems. I believe that methods should be developed to assess corrosion in the environment of interest as closely as possible (sensors, side streams, etc). This will reduce the need for complicated sampling and transport of samples prior to diagnostic measuring. I also think that as biofilms get established mechanisms other than chemical treatments and physical removal be considered. This would include taking advantage of transient environmental conditions (cold to hot or vice versa) to help disrupt/weaken established and corrosive microbial communities. This would help reduce the need for biocides/scale inhibitors.	It seems to me that there is not enough work on how best to apply biocides. Current work suggests that susceptibility of bacteria differs depending on their stage of growth. Exactly what makes a cell more of less susceptible to biocides is an important area of investigation. Ultimately, the goal will be to treat established biofilms to make them more susceptible and then use controlling biocide formulations. Since the most widely used biocides seems to exhibit multiple mechanisms of bacterial inhibition, I believe the biocide classes should be contrasted with more target control measures (antibiotics, inhibitory peptides, perhaps phage use). I also think some thought should go into designing control chemicals with particular biofilm inhibition goals (iteration on antibiotic themes that restrict microbial metabolism). Also, see answer to last question.	I think research should be cross-disciplinary with particular goals in mind. This should bridge the gap between fundamental and applied investigations. After all, biofilm formation and metal corrosion are cross-disciplinary problems. Need to reach out and partner with entities that may not be easy to categorize to advance goals. In this respect the development of in situ corrosion sensors that monitor microbial activity would be a good goal.	This depends on the goals. Conditions that weaken model cells and influence their susceptibility to biocides may be short term (1 year) and relatively inexpensive. Development of sensors can also be rapid (prototypes in 1 year), but the testing of the sensors under realistic conditions can take a long time 1-5 years). Personnel costs will also represent the most expensive part of any budget. I doubt that this will be changing anytime soon.	Much has been learned from the exploration of model systems. This is particularly true for the sulfate reducing bacteria. Mutants can be more easily constructed (e.g. thorough the use of randomly inserting transposons) to better associate molecular alterations with phenotypic responses.

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
– How to improve detection and monitoring – How to develop better/appropriate mitigation strategies – Needing better standards for laboratory test/experimental methods – How can modern molecular methods (e.g. metabarcoding) be used practically – Better communication with end users about what microbial corrosion is and isn't – Too much hearsay / folktales about microbial corrosion and need solid evidence / research to confirm claims	– More tests are required to investigate the effects of test parameters on the outcomes of MIC lab experiments – More tests are needed using multiple microbe strains, rather than just single microbe (e.g. SRB) tests	A combination of all is needed	Timescale, ongoing	
We have developed a polymer that prevents biofilm formation to surfaces without the need of antibiotics or antimicrobials. For us the key challenge is ensuring that our material can adhere strongly to potential customer surfaces and ensure that our polymer coating is durable for the application needs. This also requires us to understand when and where biofilms form so that we can target appropriate structures/ surfaces that need to be treated to prevent long term microbial induced corrosion.	The key technology that we believe can help address these issues is a preventative coating (BACTIGON) that stops biofilms from forming on surfaces. This will help to deal with the problem of MIC at the source and reduce the need the corrective treatment strategies to deal with bacterial biofilms, where are known to be heavily resistant to multiple different types of treatment. This strategy could be a part of the solution, the use of this coating strategy could be combined with chemical treatment plans at a reduced concentration to ensure that the surface stays bacteria-free. As the coating will stop biofilm formation, the chemical treatment would be more used to remove planktonic bacteria that are on the surface which are much easier to deal with compared to bacteria.	The type of research that would be required would be initial funded proof of concept studies that would cover a range of different criteria that the coating would need to be able to pass. This would include: Coating durability (both mechanical and chemical wear), efficacy to specific bacteria (both when new and used) as well as any other application specific properties that the substrate has to deal with i.e. increased flexibility for flexible tubing. This could be done through a business to business collaboration over a 2-3 month period. Following successful trials this can then be taken to larger scales to confirm efficacy in real-world scenarios.	This initial proof of concept studies would range between 1 and 3 months depending on the amount of work required and cost in the region of £5k-30k depending on the length of project. A follow-on larger scale study would then likely be performed in collaboration before commercial terms/ agreements are put in place.	What are the specific species/ strains of bacteria that cause a problem for MIC? Obviously this is very application specific but are there standard organisms that are used to show efficacy against? Is the application of new systems a suitable solution? i.e. would the solution need to work in-situ in order to save replacement of expensive parts or would industry accept the introduction new parts that need to be bought new?

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Detecting when and where they appear and finding an effective way to treatment (eg. how to to reach them in deep pipes-localised treatment)	Are there new biofilm sensors that could be used in this area? eg. sensors that detect changes in conductivity etc. There are state of the art cameras that can detect biofilms in clinical settings (lung). Could this be translated into corrosion?	Highly multidisciplinary involving engineers, microbiologists, physicist etc. It would require basic research in collaboration with industry.	This would be a long-term project with multiple research groups. Min 5-6 years and around £10M	If only 20% of the total corrosion is due to microbes. To have a much larger impact, shouldn't we be working together with research groups working on chemical corrosion to ensure we can address both issues simultaneously and more effectively?
Identifying key biomarkers for improved early detection, distinguishing between harmful and non-harmful biofilms (as not all will be destructive)	Omics technologies - metagenomics, metatranscriptomics, metaproteomics - what genes, molecules, and/or proteins are expressed when biofilms form? these could help pinpoint 'early indicator' targets	Initially basic (which would involve collaborations), but using real industry samples to make sure relevant microbial consortia are targeted/investigated.	Unknown for cost - decades for time period	
All of the above and providing tools and models that are practical and ready to use for operators in or close to the field site	Nanopore seq Machine and deep learning AI Translation to field engineers and lab staff	Applied, multi centre, collaborative with industry	The next decade £££	focus on solutions and products that will benefit industry - industrial partnership and commitment is important
Including the effect of the microbial substrate when studying MIC since most attention is Heveran to the microbial community only	An interdisciplinary approach is needed. In the last few years microbiology and related analytical techniques have been a must. Corrosion however happens on the substrate and its history is as relevant as the microbial metabolism	Advanced surface analytical methods coupled with current omits technique to produce time dependent corrosion maps	It will depend on planned actions	

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot…	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
All of the above, including especially where and why biofilms form, and where appropriate, how they can be controlled. Major challenge in understanding biofilms under in situ conditions in energy sector.	For oil and gas, role of biofilms in souring and gas extraction (especially for non conventionals). How they can be controlled in situ. How can activities be monitored in situ. In nuclear, impact of biofilms on plant operation, integrity of radioactive materials (stored or geodisposed radwaste), role of biofilms in corrosion and radioactive scale formation in pipework (major headache with some analogies to NORM in oil and gas), biocontrol strategies where required.	Basic and applied across academia-industry. Cross-disciplinary including microbial ecology/omics, imaging, spectroscopy, materials, engineering etc.	Depends on sector. Most would be midscale TRL at best, oil and gas application perhaps more advanced? Would benefit from targeted programme (multi-million £).	Explore links with BBSRC E3B Metals in Biology NIBB to access additional BBSRC support (I have a slide to introduce … will forward via email). Out of remit for meeting, but consider extending to include development of appropriate biofilm systems for bioleaching/decontamination, metal removal, recovery and revalorisation from industrial wastes etc. Downstream applications of biofilms with metals, e.g. in catalysis.
Methods for sampling and identifying key bacteria present in pipelines and their potential effect on corrosion. Finding ways to model biofilm formation in assets so that the efficacy of biocides and different treatment rates can be used in practice to lower microbially influenced corrosion rates. Better understanding of the initiation times between bacterial contamination and biofilm formation and between biofilm formation and active corrosion. This would directly assist with developing strategies for reducing the environmental impact of pipeline hydrotesting	Smaller and easy to use technologies to allow for experimentation to be performed on site Biofilm monitoring probes that could continuously monitor the formation of biofilms to ascertain the effectiveness of biocide treatments and associated cleaning programmes	Industrial collaboration to ensure that solutions are practical in the field, and to make sure that there can be helpful support and cross-pollination of ideas to get technology and ideas out of universities and use them for mutual benefit.	Ideally a prototype method within 3 to 4 years.	Understanding of chemical or other markers that show a biofilm is established and stable. Also, markers that show the degradation of biofilms. A more fundamental understanding of the way bacterial communities influence corrosion – industry focus is on groups such as SRB and misses the effects of communities within biofilms.

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Detection of active biofilms: – Confirm presence or absence of active biofilm within system – indirect observation – Narrow down location of active biofilm – Direct techniques to pinpoint biofilm location Prevention: informed by "when, why and how": – Alternate means to interrupt biofilm formation and development – need better fundamental understanding. This would be very broadly applicable, relevant to all contexts. Modify surface. Stress causes strain - different metalency - dissociation density. Model how many defects/inclusions are in metal and correlate with microbial data. MnS needed for manufacturing. Can we inhibit them once line is in place? Silicon based coatings in boats - certain speed of movement coatings - water sensing.	Novel coatings: economic, lasting, self-healing? Inter or intra microbial signaling that drives change to sessile lifestyle or induces the reversion to planktonic state. Novel non disruptive scanning tools that detect local Biofilm presence or Biofilm impact: easy to use, fast, accurate – think pin point corrosion and large areas like pipelines Sensor chemistries – a direct means to detect & ideally quantify the presence and magnitude of active biofilm Funding PhD students Mobility pilot Bring expertise together	Fundamental research on the biochemical triggers for Biofilm formation and development / biochemical triggers for biofilm shedding event leading to the ability to manipulate this. Identify causes for localized pinpoint corrosion Scanning technologies and biosensor development– engineering overlap		Pitch it both ways - alternative energy package it differently.
The key challenge in my research area is how to prevent biofilm formation. We have recently been working on the use of nanomaterials in potable water purification devices and part of the challenge is to ensure that we can deal with microbes attached to device surfaces.	A lot of work has been done on understanding the toxicity of nanomaterials to microbes but there is still uncertainty about underlying mechanisms and how microbes protect themselves. Understanding theses is key to selecting efficient materials and to designing appropriate systems.	Currently we are still at the basic understanding stage, although working with industry is key to ensure that our results are relevant and knowledge is co-produced.	3-4 years, possibly research grants totalling about £1m.	

What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Microbial biofilms remain a primary concern across engineering and medical fields. The tendency of bacterial cells to form these structures in moist environments and the resulting in numerous deleterious effects demonstrates the need for novel biofilm control strategies and innovative methods to unravel the key attachment/growth mechanisms. The extracellular polymeric substances (EPS) surrounding bacteria are fundamental components and determine the physiochemical properties of a biofilm. The EPS properties of conductivity and redox ability from an electrochemical perspective demonstrate that EPS play important roles in microbial extracellular electron transfer (EET). Microorganisms use EET processes to communicate with other cells and/or interact with external environments. Within EET pathways, microorganisms are thought to use redox proteins in the outer membrane or extended conductive flagellum/pili to transport electrons to extracellular acceptors; however, the actual mechanism of the electrical conduction that underlines this process is vague. Much remains to be learned regarding the roles of EPS in EET, as well as their effect on conductive pili or interspecies electron transfer. These pathways control diverse processes that facility biofilm attachment, antimicrobial resistance and biocorrosion.Rapid/effective enhancements in MIC understanding will require better collaboration between corrosion scientists/ engineers, electrochemists and microbiologists, in order to limit misunderstandings in terminology/definitions and knowledge transfer between the communities themselves (discussion is often lost in translation). Greater impact will be gained by working together.	Identification of the redox mediators and how these affect the anodic/cathodic reaction kinetics occurring at the metal surface.Scanning probe microscopy (SPM) techniques have proven to be powerful tools to interrogate the nanoscale properties of surfaces, and capable of studying microbial systems on both single and multicellular scales including complex biofilms. Advances in SPM-based technologies, such as the innovative electrochemical-scanning tunnelling microscopy/atomic force microscopy (EC-STM/ AFM) measurements has now allowed for the creation of a truly multi-parametric platform, enabling the interrogation of all aspects of microbial systems coupled with electrochemical studies. Developments in traditional SPM operation have allowed, for the first time, insight into the topographical landscape of microbial cells, which, when combined with high-speed AFM's ability to resolve the structure of surface macromolecules, have provided, with unparalleled detail, visualization of this complex environmental interface. The application of AFM force spectroscopies enables the analysis of many microbial nanomechanical properties including macromolecule folding pathways, microbial adhesion forces, biofilm mechanical properties, and antimicrobial/antibiofilm efficacies. Thus, EC-STM/AFM would offer outstanding insights into the biofilm, how its inhabitants create and use this complex adaptive interface, and perhaps most importantly the effectiveness of control measures.	All types of investigation are needed; bringing together expertise is a prime necessity.		

What do you see as the key challenges in respect of your sector or field? For example, is it • **knowing where, when, and why biofilms form?** • **how to elucidate coupled microbial metabolisms and pot...**	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Likewise, there is greater need to explore other MIC driven situations beyond SRB linked to the oil and gas industry. Maritime, power generation (offshore wind turbines and tidal), medical, biofuels/lubricated systems and soil environments. Also, there are difficulties in replicating MIC rates observed in the field vs. lab conditions. From an electrochemical/corrosion science prospective, key questions concerning microbial corrosion mechanisms, include: – Do biofilms affect principally either the anodic or cathodic reactions, or both, and what is the influence of redox mediators? – Are microorganisms involved in the formation of an electrochemical cell, or in its continued electrochemical function over a prolonged period? – Is the influence of biofilm growth primarily metabolic via the combined action of organisms present as a consortium, or physical through the development of diffusion gradients and microenvironments within the biofilm? – Does biofilm/corrosion product accretion have an influence on the nature and extent of any further biocorrosion? – Can localised corrosion (pitting and crevice) be the consequence of either colonial growth or development of a patchy biofilm? Here the extent of localised corrosion (assessed as diameters) on carbon steel is often discussed in terms of tens of centimetres, whereas stainless steels it would be in the order of tens of microns.				

Appendix 2: Workshop output – breakout group output (Groups 1 – 5)

Contributor	What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Group 1	Detection of MIC.Std test of MIC/CR - Regulatory environment. Complexity of corrosion processes:- Mechanistic understanding.- Correlative/ multi-factoral understanding.	Joined up interdisciplinary approaches: – Donor (key factors)/ inoculum (key organisms)/ metal (flow to make correctly) interactions – mechanisms and models. – Surface science - Spatial quality of steel. – Sensor technology. – Prevention - coatings technology.	Translation - Operational decisions from research. Global biodiversity of microorganisms impact? Metagenomics and function: Hydrocarbon degradation. Metabolomic. Biomarkers as indicators of activity. Design impacts. Failure analysis and MIC - EVIDENCE. Targeted approaches. Detection: - Corrosion, MIC and bugs. Process standards. Best practice agreed. Relevant models e.g. at pressure. Integrated approaches with improved detection. Biomarker discovery. Cycle: Assessment - control/ integration - monitoring/testing. - Metaomics integrated. Biomarkers. Quinones. O2, pH, NO3, SO4. Raman analysis. In situ sensing. Rates. Scanning electrochem microscopy - Initiation sites - Evidence based hydrogen testing protocols - Basic science/mechanisms. Surfaces: - Antifouling surfaces. - Engineered surfaces. - Novel materials: Biocides, 3D printing, textured. - Ultrasound: cleaning. - Smart surfaces. - Targeted inhibitor delivery. - Biomimicry. - Surface functionalization. - Signals dispersion anaerobes - novel control.		Inhibition.

Contributor	What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot…	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Group 2	Easier prediction and control. Differentiate acid/gas (chemical) versus MIC (bio-accelerators). Is MIC (need an assay) a major contributor? Biomarker? (early detection of developing biofilm). Higher cell numbers not always bad? Total cell numbers versus activity.		Corrosion modulators used as marker? (at metal/aqueous phase). Scale inhibitors vs corrosion inhibitors vs biodies - interplays (substrates). Biofilms (activity, adhesion) on different metal surfaces: O&G (carbon steel, steel, internal corrosion) vs maritime (internal & external, anti-fouling, tanks, heat exchanges). Detection vs Prevention: – Detection: Biomarkers in collectible H2O. Improved monitoring coupons that provide real-time biofilm corrosion activity. Predict improved coupon placement. Predictors for H2O dropout along pipeline for low/heavy oils. – Prevention: Novel biocides of novel action. Cost prohibitive? Bringing expertise together at the beginning of experimental design. Sharing of data and results (historical data). Differentiating chemical vs MIC: – Basal rates: Temporal profile of behaviour of surface chemistry. – Standardisation of methods to determine multifactoral modulators. Tractable and relevant reactors. – Surface material and reactivity. – Solution chemistry. – In situ data. In situ monitoring/detection of telemetry. MIC related activity common to major functionalities? Aerobic and anaerobic. Electron scavenging. H2 detection. 'Exotic metal species' e.g. Hi, W, B. N2 fixation (breakdown of chemistries added).	15 years (2034) $1million per year per activity.	

Contributor	What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Group 3	Role of metallurgy in biofilm formation? And how can we use this information? Application to real world scenarios. Massive gap between what we can do and what we are doing. Regulation.	Future materials e.g. carbon steel, stainless steel. Future prevent e.g. electrons going to biofilm.	2-3 disciplines and 10-15 people: Materials guru. Physicist (bio background). Electrochemist, chemist. Geologist. Microbiologist. End users (industry) - samples and insights. Data scientists and engineers. Pipe microbiome data - metabolomics/ access to samples [where and when]/ biocide impact - coupon/water - MIC potential.	3-4 years. £5M and in kind.	Iron biologically available? MIC programme manager - saving money. Teams - Papers, iCASE, undergraduate forum.
Group 4	Detection of corrosion. Chemical vs biochemical. Standardisation. Monitoring in large networks - needs to be high throughput or real time. Coupon monitoring does not show differentiation between chemical and microbial. Remote sites cause logistical issues - real time or close to it would be useful but difficult. Time constraints cause treatment for chemical and microbial regardless of results. Sea water injection causes huge issues for monitoring. Engineers find it difficult to quantify which type of corrosion is the most important. Interplay between microbial and chemical corrosion not well understood. Bacterial contamination hard to differentiate. Lack of operational staff education. Need biomarkers to monitor.	Smart pigs - Inline sampling - Using markers to measure thickness. Trial in well before deploying into the line - using well bores and guess. Training and education. How to deliver networks delivering awareness? Cathodic protection - For Fe^{2+} to release, the electrons must find somewhere to go - ends up at biofilm. Should we consider something in the pipeline that receives these electrons and therefore cannot contribute to biofilm formation/growth? (Norway coast). Pipeline microbiome - can we pool all the data? How could this be useful to NBIC researchers? Pearlife bands. Microgalvamic acidifiers. Inhibitor layer. AFM techniques. Kalvin probe surface. EMIC Metabolomic biomarkers. APES	Developing programmes to address the relevance of MIC vs chemicals and corrosion rate studies. Water line systems could be an easier place to start. Biosensors for real time results. Simulation. Convincing to carry out sustained and periodic maintenance - Frame around cost of biocide or regulatory environment. Biofilm instead of removal. Oil and gas UK Service Sector Body - Centralised research. Target most corrosive environments. MURI - Multi Univ. Research Infrastructure. Inline inspection (every 5 years e.g. ultrasound tests).	Field operations only allow 2-3 years for solutions. Should only be approached when you're ready.	Biomarkers

Contributor	What do you see as the key challenges in respect of your sector or field? For example, is it • knowing where, when, and why biofilms form? • how to elucidate coupled microbial metabolisms and pot...	What is the emerging science and technology that you feel could be investigated/ translated to address these challenges?	What types of research/ investigation would need to be done on these e.g. basic, applied, multi centre, collaborative with industry?	What cost and timescale might this be?	Are there any research questions or fundamental science that needs to be investigated that you haven't already covered?
Group 5	Realistic experimental systems. Not just 'biofilms'; specifically corrosive biofilms? How to identify hotspots. Link between microbiology and molecular science. Correlation to corrosive propagation, to defects, growth structure in metal. Other physical properties. Microstructure of metals. Coupled models of biofilm models and corrosion models.	Passivation of "hotspots" - remove this e.g. used for manufacture. Standardisation of metals – actually have quite a lot of variation. – "Real time" continuous monitoring - baseline data and look for deviation from the baseline. – Database of 'corrosion' vs metal types. – Prevention through materials? Replenary infrastructure unforeseeable. Maybe long term for the future. Where, when and why?: – Relationship between material properties and maturation of biofilm growth. – Not just biofilm, why specifically corrosive biofilm. Elucidation microbial metabolism/biomarkers: – Important to know mechanisms at that can inform where, when and why. – Inform control strategies. – Really important theory is the 'TRANSLATION'. Monitoring and detection: – Informed by understanding mechanisms and processes. – Better/cheaper monitoring technologies - allow high frequency monitoring - baseline deviation. Prevention: – Importance of retro-fittable solutions. – Replenary infrastructure is a much much longer timescale proposition. Oil and gas focus today but also for offshore wind structures and water industry. Other theory: 'Mindset challenge'. Timescales of translation vs timescales of industry.	We know that the science and technology exist to tackle the questions. The challenge is how to bring the different parts together: – Link programmes. – Prosperity Partnerships. – Royal Society Industry Fellows. – Innovation fund for more focused 'near models', 'Big ideas'. – JIPS - leverage. Think about it in the trillions levels. Funding strategy may be different: – 1-3 Basics of understanding biofilm formation. – 4-6 A lot of activity in that area. – 7-8 Not so much in that space.	PhD - £3-5 million Consortium with multiple industry/ academic partners	Community forum 'village' Combine output from meeting and form then cycle with synthesis and update. NIBBS IBBS Montana September 2020.

Thank you

For further information please contact nbic@biofilms.ac.uk