Degradation in structural materials for net zero

A landscaping exercise

This report is commissioned by the Henry Royce Institute for advanced materials as part of its role around convening and supporting the UK advanced materials community to help promote and develop new research activity. The overriding objective is to bring together the advanced materials community to discuss, analyse and assimilate opportunities for emerging materials research for economic and societal benefit. Such research is ultimately linked to both national and global drivers, namely Transition to Zero Carbon, Sustainable Manufacture, Digital & Communications, Circular Economy as well as Health & Wellbeing.

INSTITUTE OF CORROSION
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Executive summary

The target of achieving net zero by 2050 is both laudable and ambitious, but the efforts required to reach this goal are substantial and will have an impact on nearly all aspects of life. Simply setting this target is not enough however, we also need to implement ways to ensure we achieve it by making key decisions and taking actions now.

For many sustainable and low carbon technologies, the degradation of structural materials presents significant and ongoing challenges, limiting the performance, operational life, and sustainability of assets.
Indeed, the financial burden caused by corrosion, which represents just one of the mechanisms under the umbrella term of degradation, was estimated to be $2.5 trillion, or 3.4 % of the world's total gross domestic product (GDP) in a 2016 report by NACE [1]. With such large sums involved, the UK will only harvest the maximum benefit from the race to achieve net zero by implementing a coordinated, coherent and consistent approach, driven by high-level leadership, owning and defining the best and most strategic pathway towards this goal. Agenda setting is the Government's prerogative and only by identifying cross-sectoral synergies and issues will the most cost-effective route to net zero be successfully navigated [2].

This report presents the results of a landscaping exercise conducted by the Henry Royce Institute, Frazer-Nash Consultancy, and supported by the Institute of Corrosion during spring 2021. Using input from a steering committee consisting of materials science experts, the report identifies and explores the critical structural materials degradation challenges in meeting net zero 2050. Presented herein are the findings from key stakeholder engagement activities across the following five industrial sectors:

- Nuclear fission
- Wind (both on-shore and off-shore)
- Hydrogen
- Carbon Capture and Storage (CCS)
- Transport (aerospace, rail, road, sea).

> ***"For many sustainable and low carbon technologies, the degradation of structural materials presents significant and ongoing challenges, limiting the performance, operational life, and sustainability of national assets."***

Engagement with stakeholders was achieved through the development and distribution of a survey which gathered expert opinions on the degradation of structural materials. The findings from the survey were then clarified and discussed in detail in a technical review meeting that was held with survey respondents.

Three major, common, cross-sector degradation mechanisms were identified in response to the survey:

1) Corrosion
2) Fatigue
3) Creep

While this is not a revelation as such, their consistent appearance affirms their critical cross-sector importance in the context of achieving net zero 2050 and should inform the optimisation of appropriate R&D programmes.

In addition to corrosion, fatigue and creep, the exercise also highlighted the increasing relevance of interactions between these mechanisms which needs focused research. The degradation mechanism interactions identified by the exercise were:

- Aqueous corrosion fatigue and stress corrosion cracking
- Creep-fatigue
- High temperature corrosion/oxidation and fatigue
- Stress assisted corrosion and oxidation mechanisms
- Environmentally assisted creep crack growth.

These interactions are largely the result of the requirement for structural materials to operate under increasingly challenging conditions with higher temperatures and exposure to harsh environments, such as carbon dioxide (CO_2) and hydrogen (H_2).

These mechanisms are not only significant in achieving net zero but are also responsible for significant disruption and expense to society. The degradation of assets leads to potentially dangerous failures, downtime and repairs with high costs both financially and to the environment. Some recent examples are:

- Ørsted have reported that subsea cable erosion of an offshore wind farm has cost the project up to £350 million to rectify
- Rolls Royce Trent 1000 turbine blade durability issues are estimated to cost up to £2.4 billion between 2017-2023
- A benefit to the economy of £108 million per reactor per year was generated through extending the life of the UK's Advanced Gas Reactors
- Fatigue issues in Class 800 series Hitachi trains are estimated to cost between £1 - £2 million per day.

Therefore, significant savings can be achieved through better understanding and effective management of degradation issues.

This landscaping exercise has confirmed that there is a strong resolve to address the degradation issues presented by the transition to net zero across the materials and wider engineering and scientific community. However, in many sectors, there are a wide range of technologies often in competition with one another. In order to provide both confidence for investment, and a sense of purpose for the research community, there is a need for high level strategic direction. This direction will help to guide R&D efforts to address these degradation challenges, through a clearly communicated strategy based around a holistic approach. In order for such a strategy to have authority and credibility, it is imperative that it should be developed as a collaborative effort between senior policymakers, along with a broad range of cross-sectoral academic and industrial stakeholders.

This report identifies six key areas for investment, which will provide cross-sector benefits and where systematic work is required to address degradation mechanisms, namely:

1. **Design and manufacture:** For improved sustainability across the life cycle of assets, consideration of material degradation is equally as crucial at the design and manufacturing stages as it is throughout the operational life.
2. **Modelling and simulation:** Integration of simulation techniques and modelling are of increasing importance in solving complex materials degradation problems.
3. **Maintenance and inspection:** Improved, updated, informed and properly formulated inspection and monitoring techniques will support life extension activities and enable industry to adopt new materials and manufacturing methods.
4. **Characterisation and testing:** In order to effectively address and manage degradation challenges and issues, there is a need for an improved fundamental understanding of the degradation mechanisms.
5. **Knowledge and data management:** Initiatives to encourage knowledge and data sharing are required help support the development and implementation of new net zero enabling methods and technologies.
6. **Leadership and policy:** Direction and clarity on strategy is paramount to provide focus and promote investment in new technologies and methods. Providing incentives through challenge-driven research projects are great structures to foster successful and broad collaboration. Employment of a model similar to that used in the Faraday battery challenge is an excellent template upon which to build a comprehensive funding strategy to tackle cross-sector degradation of structural materials.

To meet the challenges and fully realise the opportunities which exist across these areas in a focused, efficient, and effective manner it is suggested that it is the last point on leadership and policy which is most important. Collaboration between governing bodies, UK Research and Innovation (UKRI), major industry players, the supply chain, the Department for Business, Energy and Industrial Strategy (BEIS) and academia is essential. This will require promotion and encouragement through focused initiatives, communicated from a senior leadership position to prevent things “falling through the cracks”.

This approach will naturally involve leveraging existing infrastructure and projects such as those below, which have received significant investment to date:

- The high-value manufacturing catapults, such as the Nuclear Advanced Manufacturing Research Centre (NAMRC), the Advanced Manufacturing Research Centre (AMRC), the Manufacturing Technology Centre (MTC), the Advanced Forming Research Centre (AFRC) and the National Composites Centre (NCC), can be leveraged for design, manufacture, and high Technology Readiness Level (TRL) testing
- The Royce Institute facilities and expertise can be leveraged for materials’ characterisation and low-TRL research and innovation
- National Physical Laboratory (NPL) can be leveraged for the development of standards and certification
- The Knowledge Centre for Materials Chemistry (KCMC) and the Sustainable Materials Innovation Hub (SMIH), can be leveraged to help implement elements of a circular economy approach to design and manufacture of structural materials
- The Science and Technologies Facilities Council (STFC), can be leveraged to help coordinate research efforts
- The wider catapult network such as the Offshore Renewable Energy (ORE) catapult Energy Systems and Digital catapults
- The Aerospace Technology Institute and the Advanced Propulsion Centre for low carbon powertrain technologies
- Other pertinent organisations and centres of excellence, such as The Faraday and Alan Turing Institute.

It is this ready and capable infrastructure, which provides justification for the UK being ranked consistently highly on its R&D landscape and ability to understand materials degradation mechanisms in the survey responses. However, what is also clear from this study is that the UK struggles to commercialise and export this excellence and capability.

While recent successful initiatives such as Transforming the Foundation Industries, under the Industrial Strategy Challenge Fund, appreciate the need for cross-sector collaborative projects, these remain short duration in nature. It is also the case that funding calls continue to encourage an isolated approach to investigating degradation mechanisms within particular systems.

Out of the six key areas identified for cross-sector investment above, this report recommends that only with a significant change in leadership and policy will the obvious opportunities for transformational change be grasped and ultimately realised.

It is proposed that a technology roadmap would be an effective way to communicate a clear strategy and direction to the materials and materials degradation community, by identifying key technologies and delivery dates helping to guide investment decisions and inform strategic R&D activities.

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1

Introduction and context

Achieving the UK government's pledge of net zero 2050 requires focused R&D initiatives and programmes, as identified by the UK Research and Development Roadmap.

1.1 Reaching net zero and motivation for structural materials degradation research and development

The world is in the midst of an international effort to reduce greenhouse gas emissions in an attempt to limit the impact of climate change, with many governments committing to targets in carbon reduction in order to achieve this. The UK government has signed legislation committing to a target of net zero contribution to global warming by 2050 [3], and, in the interim, to reduce emissions by 78% compared to 1990's levels by 2035 [4]. While these commitments present a significant challenge, their scale and global nature provide unique and unprecedented opportunities to develop and lead in new and advanced technologies.

To reach net zero by 2050, a holistic view of industry and the lifecycle of assets, from conception through to decommissioning and recycling, is fundamental, as highlighted by the UK Industrial Decarbonisation Strategy [5]. This was also identified in a review published in Nature [6] on the strategies for improving the sustainability of structural metals, which highlights addressing the degradation of metals as a key area with significant potential for carbon reduction.

Degradation of materials has a substantial economic impact around the world. As an indicative example, corrosion is just one such category of a degradation mechanism, but has a likely economic impact equivalent to several percent of world GDP. A breakdown of the relative cost of corrosion is presented for several countries in Figure 1.

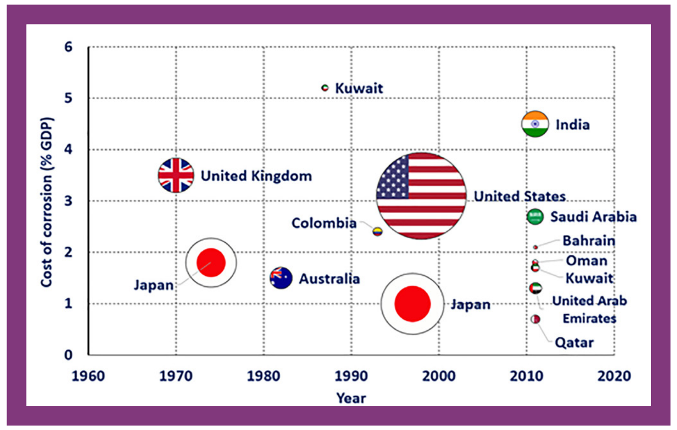

Figure 1: Cost of corrosion as a percentage of GDP, where bubble areas are scaled based on the cost as a proportion of world GDP using data from the NACE Impact Report 2016 [1] and the World Bank [7].

These figures are influenced by a number of factors, such as each country's level of development, climate, and industrial landscape. However, the consistent significance of corrosion as a proportion of GDP demonstrates the importance of degradation and the opportunity for cost reductions and increased sustainability.

1.2 Scope and approach of this document

This document reports the findings of a collaborative landscaping exercise, focused on the degradation of structural materials across five sectors crucial to the delivery of net zero. It aims to identify the opportunities for both targeted investment to enable accelerated decarbonisation within the UK, and those which could help establish the UK as an international leader in sustainable technologies. By engaging with stakeholders across academia and industry, through a survey and subsequent technical review meeting, this report presents the landscape as described to the authors by experts who deal with degradation on a daily basis. It is important to note that the report herein is neither an exhaustive review nor a roadmap.

The selected five industry sectors align with the government's 10-point-plan for a green industrial revolution [8] and are:

- Nuclear Fission
- Wind
- Hydrogen
- Carbon capture and storage (CCS)
- Transport (aerospace, rail, road, sea).

Several factors underpin the particular focus on these sectors:

- Hydrogen, CCS, Wind and Nuclear Fission are important technologies for the production of low carbon energy, and aiding in the decarbonising of industry [9]. However, R&D is required in order to scale these technologies up (in terms of nuclear this refers to advanced reactors), and maximise their operational life, performance, and sustainability
- Transport is a sector responsible for high levels of greenhouse gas emissions [10], and requires innovation and new technologies in order to reduce these emissions
- Significant synergies are prevalent across these sectors in terms of technology application (such as gas turbines) which provides a solid bedrock upon which to build collaborative consortia for cross-pollination of ideas and experience.

Structural materials degradation is inherently a broad subject area, involving many aspects and technical disciplines. This work intends to inform and identify, through stakeholder engagement, where there is a need for technical research or opportunities for greater collaboration and also where more detailed studies and road mapping activities would be of most benefit.

Due to the tight time scales of the exercise, engagement of stakeholders from academia and industry was conducted through a targeted survey, which is described in Section 1.4. The findings from this survey were then followed up with a technical review meeting to discuss and agree the outputs. The objectives of this report are as follows:

- Provide the current landscape of degradation issues that are prevalent in the five selected industry sectors
- Present the findings, opportunities, and challenges from the stakeholder engagement activities
- Provide commentary on the implications and recommendations of the findings.

The report presents sector-specific findings in Section 2. These provide the context for each sector, alongside the opportunities and challenges which were identified by the exercise.

The cross-sector opportunities and challenges are presented in Section 3, and identify six key areas which are instrumental to the net zero goal and require structured research and investment.

The overall conclusions and observations from the exercise are presented in Section 4.

1.3 Survey findings and analysis

As outlined in Section 1.2, a survey was used to gather initial input from industrial and academic stakeholders to inform the subsequent review meeting and discussions (see Annex A). Three broad topics were covered by the survey:

- High-level opportunities
- Specific material degradation challenges impeding progress to net zero
- The UK's capability and readiness to exploit the challenges identified by the respondents.

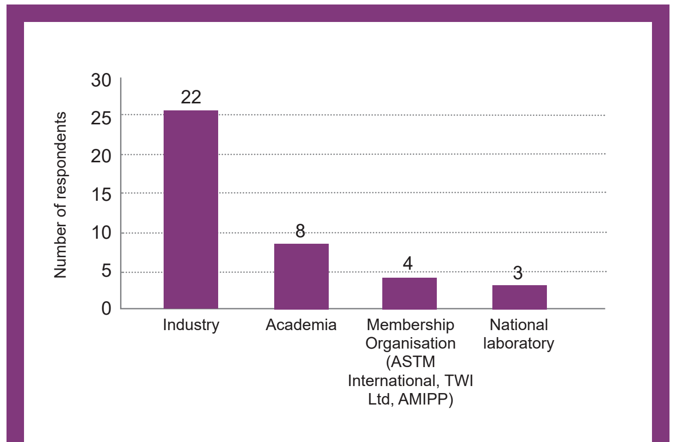

Figure 2: Survey respondent's organisation

High quality responses to the survey were provided by 41 experts from across 37 organisations (Figure 2). The respondents' areas of expertise are presented in Figure 3, where many of the respondents had expertise across several sectors.

Importantly, the survey did not identify any degradation issues which would prevent the UK achieving net zero by 2050. However, a number of challenges and opportunities which require incremental investment and work were identified and are discussed in Section 3 of the report.

Unsurprisingly, three common degradation mechanisms (corrosion, fatigue, and creep) were mentioned repeatedly in the survey responses (Figure 4), affirming their relevance in the context of achieving net zero 2050.

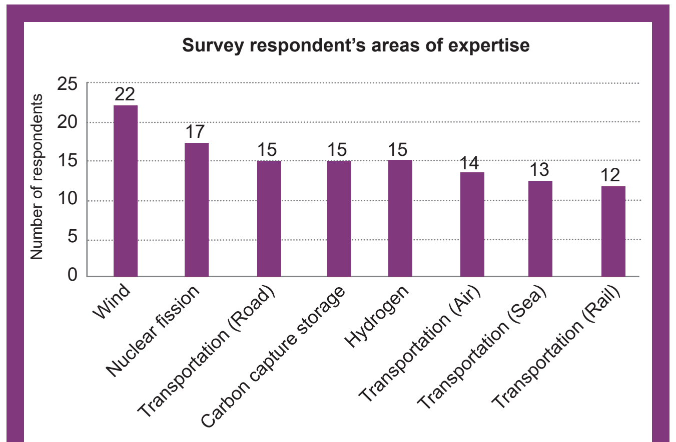

Figure 3: Stakeholders and survey respondent's areas of expertise

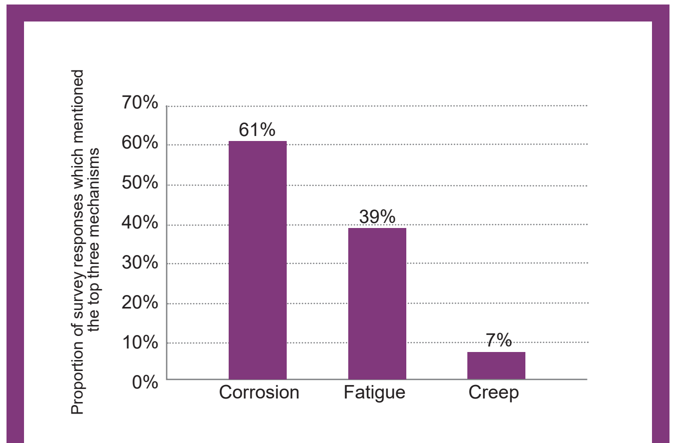

Figure 4: The proportion of survey responses which mentioned the top three mechanisms

Another common theme raised was the future requirement for materials to operate in more challenging environments. This gives increasing importance to interactions between the three mechanisms noted above and others such, as environmentally assisted fatigue, stress assisted corrosion, and creep-fatigue.

In response to the UK's capability and readiness to address the opportunities and challenges identified, survey respondents demonstrated a consistent belief that the UK is very well placed to undertake research into degradation mechanisms. However, there was also a consistent view that the UK is less effective at developing and commercialising research. Since the majority of the respondents were from industry (Figure 2), this is an important observation, highlighting the need for targeted funding to help bridge the gap from research and development to commercialisation.

The survey and wider exercise was successful in identifying the opportunities which fall into the following categories of the innovation landscape, as graphically presented in Figure 5:

Q1: Where there are opportunities to better apply existing ideas and techniques to known problems/challenges
Q2: Where novel ideas/techniques can be applied to known problems/challenges, and
Q3: Where existing ideas and techniques can be applied to new problems/challenges.

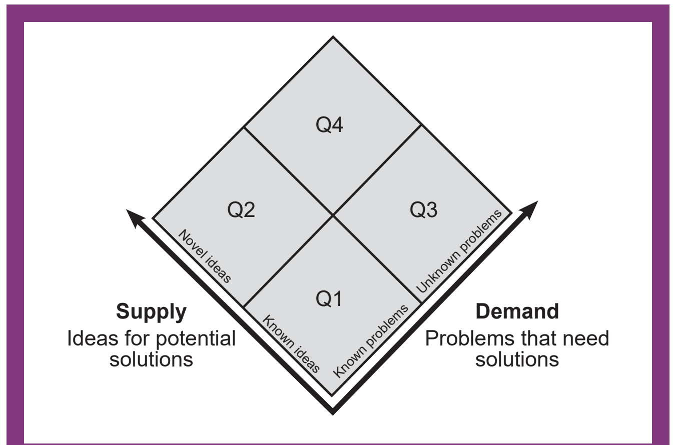

Figure 5: Innovation landscape

However, understanding where novel ideas/techniques can be applied to new/unknown problems/challenges (Q4) is difficult. This is made particularly challenging if understanding both the problems and the ideas is highly multidisciplinary. While there is no easy solution to this problem, ongoing collaboration and cross-pollination across sectors and disciplines is likely to continue to play a key role.

2

Sector by sector review

The survey responses have been grouped together on a sectoral basis to provide an exploration of the aspects of degradation particular to each industry.

The responses were then collated under four distinct sub-categories which were commonly identifiable to all five sectors. The four sub-categories, labelled below, have been used to provide a consistent structure to discuss the survey findings relating to the lifecycle of assets:

1. **Design and manufacture:** New asset introduction, product development, joining techniques, and new manufacturing processes;
2. **Operate and maintain:** Operational life of assets and systems;
3. **Decommission and disposal:** End of life activities such as decommissioning, recycling and disposal (note that for CCS and hydrogen many of the decommissioning and disposal challenges have not yet been broached);
4. **Fundamental understanding:** This is an underpinning category which discusses particular degradation mechanisms and feeds into all of the above, including test programmes, characterisation, and *in-situ* accelerated testing.

2.1 Nuclear fission

2.1.1 Context and introduction

Nuclear is a mature low carbon technology, with new nuclear being identified as a fundamental technology for the delivery of net zero in point three of the Ten Point Plan for a Green Industrial Revolution [8]. The NIRAB report on The Role of Nuclear Energy in Decarbonisation [11] proposes three waves of new nuclear technology, each coming on-line at different points over the coming decades. These consist of:

- Large-scale light water reactors (LWRs) such as Hinkley Point C (HPC)
- Small modular reactors (SMRs) which are based on the same proven technologies as LWRs, and
- Advanced Modular Reactors (AMRs) which typically have higher temperature output, enabling them to contribute to decarbonisation of the three energy vectors of electricity, heat and (production of) hydrogen.

> ***"Nuclear is a mature low carbon technology, with new nuclear being identified as a fundamental technology for the delivery of net zero."***

As the UK's current fleet of ageing Advanced Gas-cooled Reactors (AGRs), which currently contribute 9GWe, come off-line by 2030, there is a clear need for new nuclear to (at a minimum) replace this contribution, and ideally increase in capacity.

Nuclear power stations suffer from structural material degradation over the course of their operational life. The economic impact of the life extension of nuclear reactors through managing material degradation has been confirmed by the Chief Graphite Engineer at EDF [12] as resulting in direct economic impacts of £1.5 billon per annum and generating supply chain income within the UK of £650 million per annum. In relation to CO_2 emissions and environmental impact, the life extension of nuclear reactors has resulted in the avoidance of more than '42 million tonnes of CO_2 emissions up to July 2020' (>17 million per annum) through the provision of ~7.7 GW net of low carbon emission electricity.

2.1.2 Opportunities and challenges

2.1.2.1 Design and manufacture

Considerations for nuclear new build projects

New nuclear build provides opportunities for:

- Significant cost reductions
- Reduced environmental impact associated with infrastructure
- Longer service life compared to the last generation of nuclear facilities.

In order to realise these opportunities, there is a need for R&D across multiple areas and disciplines, including materials degradation. The NIRAB report [11] identifies some of the other areas which require R&D for the full potential of new nuclear to be realised.

Nuclear new build projects are also crucial to support the co-delivery of additional deep decarbonisation pathways, such as heat and hydrogen energy vectors. These pathways contribute to reductions in emissions, but also place increased demands on the operating conditions of nuclear fission facilities.

Alongside nuclear new build projects, there needs to be concurrent development of energy storage technologies, so that fluctuations in the electricity generated from renewables (solar/wind/water) does not require supplementation from nuclear. The start-stop operation this demands from nuclear increases the cyclic loading and degradation of nuclear facilities.

Advanced manufacturing and joining techniques

The implementation of new manufacturing and joining techniques, such as additive manufacturing (AM), electron beam and laser welding, present opportunities in supporting the delivery of major infrastructure projects within the desired costs and time scales. A better fundamental understanding of these techniques and their degradation performance is needed for their future use, supported by materials testing, characterisation, and modelling R&D activities.

2.1.2.2 Operate and maintain

Challenges in degradation life assessment methods in nuclear new builds

R&D and operational experience have built up methods and processes for life assessment, which in the UK is documented in nuclear industry procedures and standards such as R5 and R6 [13] [14]. However, for higher temperature new build and long term plant operation, challenges still exist which need future investigation and R&D.

AMRs will be required to operate at much higher temperatures than AGRs (>500 C) and, as a result, the degradation mechanisms are likely to be dominated by high temperature creep and creep-fatigue in existing and future alloy systems. The survey results demonstrated that concerns exist that the UK currently lacks sufficient practitioners with in-depth knowledge of the degradation mechanisms when irradiation and high temperatures combine. The combination of these environments give rise to stress corrosion cracking (SCC), fatigue, creep, and creep-fatigue. These mechanisms will need to be much better understood when the UK makes a decision on the AMR technology and/or technologies it wishes to pursue [15].

In addition to increased operational temperatures, the requirement for more flexible operation following the energy network transition to renewable sources, will result in increased numbers of cycles, with implications upon life and degradation assessments.

To address these material degradation challenges in new nuclear, extended materials testing databases are needed for high temperature operation under irradiation (e.g. in prototype, very high temperature reactors VHTRs for explicit hydrogen co-generation). The value of such material testing could also be advanced in combination with detailed studies which use *in-situ* monitoring of microstructure evolution while X-ray diffraction (XRD), measurements can provide new levels of understanding of these mechanisms at the micro-scale.

2.1.2.3 Decommission and disposal

Degradation of nuclear waste disposal facilities

The management of nuclear waste is a key factor in persuading the public to accept expansion of nuclear power. There are a number of disposal concepts for high level waste, intermediate level waste and spent fuel. Considerable research has been conducted on the design and understanding of corrosion of waste containers, both in the UK and overseas, over the last 40+ years.

There are still some outstanding issues which need further exploration, such as understanding the effects of microbial pollutants and corrosion, and demonstrating the durability of disposal concepts in real underground environments and laboratory experiments, given the Government's expressed desire for a geological disposal facility (GDF).There is also a need to carry out site-specific research in the UK on the local environmental conditions to evaluate the corrosion behaviour of the chosen design at the identified site.

2.1.2.4 Fundamental understanding

Exploitation of AGR and post-irradiation examination expertise

The UK has developed expertise through decades of operation of graphite-moderated AGRs via the last major nuclear building programme during the 1970s and 80s. Coupled to this is a world leading capability in post-irradiation examination based in academia and national laboratories. Exploitation of this competitive advantage can be harnessed by applying this understanding of degradation in alloy systems in future designs.

Understanding degradation mechanisms in new nuclear

Degradation challenges remain that could prevent the UK from realising cost reduction and decarbonisation of new build nuclear.

In LWRs, irradiation results in the degradation of the structural integrity of the ferritic reactor pressure vessel (RPV). As the RPV is irreplaceable, this phenomenon can be life-limiting for the entire reactor. Furthermore, stress corrosion cracking affects RPV internal stainless steel components, while environmental fatigue impacts upon piping and associated components. LWR nuclear fuel is clad in Zr based alloys, and therefore a holistic understanding of Zr-cladding degradation mechanisms (corrosion, hydrogen pickup, pellet/cladding interaction, hydride cracking etc) would help maximise fuel efficiency and reduce waste.

In AGRs, radiolytic oxidation of the graphite bricks leads to loss of structural integrity and is a life-limiting factor for power stations. Improved understanding of the links between microstructure and properties under irradiation is needed for plant lifetime extension. This is particularly relevant to potential Gen-IV systems, such as graphite-moderated VHTRs.

> *“Degradation challenges remain that could prevent the UK from realising cost reduction and decarbonisation of new build nuclear.”*

Simulation, modelling and analysis

Simulation, modelling and analysis are currently used in the nuclear sector to support materiallife protocols, advanced manufacturing development, and to supplement materials testing programmes. For new nuclear, there is a need for the development of simulation techniques of the combined material degradation modes of irradiation, creep, fatigue, SCC, to both minimise testing and speed up implementation of new materials and manufacturing techniques.

2.2 Wind power generation

2.2.1 Context and introduction

Renewables provide nearly a third of power in the UK, and half of this is generated from wind energy, with an installed capacity in 2019 of approximately 14 GW and 10 GW for onshore and offshore wind respectively [16].

Two types of wind power generation are considered in this section of the report; onshore wind and offshore wind.

Onshore and offshore wind

Onshore wind is reported to be less expensive than other renewables, gas, nuclear, and coal [17]. Wind is considered a clean power generation technology, receiving high levels of public support [18]. The impact from investment in onshore wind in the UK has been cumulatively calculated as £35 billion across the 1,500 operational onshore wind farms [19].

The UK is also heavily invested in offshore wind, where it has been reported that the UK has more installed offshore wind capacity than any other country [20]. Since the cost of new offshore wind has fallen by 50% since 2015, it is one of the most competitive options for renewable power in the UK [21].

The degradation of wind turbines is a costly issue; Ørsted have reported that subsea cable erosion of offshore wind farms has cost up to £350 million to rectify [22]. In addition to limiting the lifetime of wind turbines, the degradation of turbines has been estimated to result in a 1.6 % reduction in power output per year [23], leading to losses in revenue. Therefore, improved understanding, prediction, and management of this degradation within the harsh environments in which wind turbines operate has the potential to provide huge cost savings and benefits to the wind and energy industries.

2.2.2 Opportunities and challenges

2.2.2.1 Design and manufacture

Standards for building foundations

The survey highlighted that no clear standards for building foundations are currently available. The development of such standards is important to realise maximum benefit from wind power generation and ensure structural integrity. The development of standards relies on collaboration between original equipment manufacturers (OEMs), contractors and operators.

2.2.2.2 Operate and maintain

Sharing and availability of data

Survey respondents noted that there is a reluctance for both equipment manufacturers and operators to share data, due to potential commercial implications. This is further complicated by the fact that many of the manufacturing companies are owned by overseas entities. Without this exchange of knowledge and transparency, it will remain difficult to have a comprehensive understanding of full life cycle issues and how to manage them effectively and efficiently.

The industry would almost certainly benefit from an international forum where equipment manufacturers and wind turbine operators can share and discuss design and operating data, to enable the holistic degradation picture to be understood.

Utilising understanding from other sectors

The development of wind power has naturally been driven by the power industry, with a focus on electricity generation. However, the continued expansion and maintenance of wind requires a broader range of expertise, including corrosion and degradation.

A pipeline of technicians who understand the degradation mechanisms for wind turbines is needed to develop mitigation programmes and provide ongoing monitoring and inspection. Engineers are required who can design improved structures and life extension programmes.

A number of survey respondents commented that there is currently a lack of corrosion and mechanical integrity professionals in the wind industry and that this is consequently having a deleterious impact on down-time and repair of operational windfarms. There is a clear opportunity therefore to utilise professionals from the oil and gas industry who have managed similar degradation problems for many years, to ensure cross-sector pollination of knowledge. Of course, there are differences which must be understood, but the central argument remains

that a siloed approach to industry is causing unnecessary increases in cost and waste, which is an inefficient use of resources.

Wind turbine structural integrity in harsh environments

Offshore wind turbines are composed of a number of structural components which are either continuously in contact with sea water or exposed to regular sea spray. Sea water can also migrate to the inside of the structure, making it vulnerable to both internal and external corrosion. It is the case that all metallic parts of the turbine structure are susceptible to corrosion, including boat landings, stairways, handrails, and electrical cables.

There is a need to better understand fatigue and corrosion-related fatigue in wind turbines, which results from stresses produced by the environment (wind, wave, and currents) as well as the cyclic loading of the rotating turbine blades. Additionally, many wind turbines employ concrete in their foundations and structures and the degradation of concrete exposed to sea water has been highlighted as an issue which needs better understanding over the lifetime of the wind turbine.

Life extension

The UK has a large inventory of installed wind structures, some of which are now coming to the end of their original design life and will require life extension through inspection, monitoring and analysis. Since the life cycle is not fully understood, the options to extend life are not clear, with a lack of guidance, and standards to inform these activities.

Inspection guidance

Whilst degradation is a known issue, it was felt that improvements could be made to inspection and monitoring regimes through the operational life of wind turbines. Methods and guidance are required to help inform targeted inspection routines and intervals (noting that there are significant operational and capital costs associated with inspection and monitoring of wind turbines).

2.2.2.3 Decommission and disposal

Wind turbine blade recycling

Current composite blades cannot be recycled, which is wasteful and generates significant amounts of landfill [24]. This is currently an area under research [25] but there are no definitive solutions on the table yet; as such, this presents both a challenge and an opportunity for improvement in terms of sustainability.

Standards for decommissioning

The survey responses highlighted that no clear standards for the safe and efficient decommissioning of wind structures are currently available.

2.2.2.4 Fundamental understanding

Research and development activities to address the structural integrity challenges

Research and development is required to better understand and generate test data for the key degradation issues related to wind structures.
These can be summarised as:

- Corrosion and corrosion fatigue of metallic structures (in and out of sea water). This requires specialist testing with environmental test rigs and characterisation, as well as longer term testing programmes
- Manufacturing turbine blades that can be recycled. This requires collaboration between materials research facilities (such as the National Composites Centre) and manufacturing to develop suitable recyclable materials which can withstand harsh off shore environments
- Degradation and erosion of composite turbine blades, as well as the effect on lifetime of fluids, such as sea water, hydraulic fluid, and antifreeze chemicals are not well understood. There is therefore a need for testing to inform life assessment models, and the development of prevention methods for blade erosion
- Methodologies to improve predictions of the life of structures. This requires modelling and simulation activities, supported by materials testing and operational data acquisition to inform designs which support life extension and repair/replacement.

> *“Research and development is required to better understand and generate test data for the key degradation issues related to wind structures.”*

2.3 Hydrogen

2.3.1 Context and Introduction

Hydrogen is point 2 of the UK Government’s Ten Point Plan for a Green Industrial Revolution [8] which aims to drive the growth of low carbon hydrogen as a ‘clean source of fuel and heat for our homes, transport and industry’. In order to meet this need, there are lots of research facilities and organisations actively supporting the development of hydrogen in the UK. These are identified on page 2 of the materials for end-to-end hydrogen report [26].

Current hydrogen usage is dominated by industrial processes such as oil refining, and production of ammonia, methanol and steel. Opportunities for future applications of hydrogen include heavy duty transport (particularly shipping and aviation), commercial and residential heating, and power generation.

Production of hydrogen can be divided into three main categories:

- Grey: Hydrogen produced from fossil fuels, with significant carbon emissions
- Blue: Grey hydrogen coupled with CCS to sequester emitted CO_2
- Green: Low emission hydrogen produced using clean energy sources.

In order to deliver upon hydrogen’s promise as a clean energy vector, significant effort is required to reduce reliance upon grey hydrogen, and instead move towards some combination of (cost-effective) blue and green hydrogen production. In particular, green hydrogen generation, coupled with clean power sources (especially wind and nuclear), offer significant opportunities to help decarbonise the production of hydrogen.

2.3.2 Opportunities and challenges

2.3.2.1 Design and manufacture

Repurposing existing infrastructure

Significant opportunities exist to repurpose existing infrastructure (with some modification), such as gas compressors, pipelines, and distribution networks, for use as part of the hydrogen economy, as identified in Section 3 of the report 'Materials for end-to-end hydrogen' [26]. However, the risk of hydrogen embrittlement of repurposed gas grid materials is not fully understood. Deep understanding of the effects of hydrogen on the degradation and future performance of repurposed infrastructure under realistic exposure conditions is vital to safe and effective operation. In addition, appropriate inspection and life extension techniques are required to determine suitability of existing metallurgy for reuse.

Materials for liquid hydrogen storage

Low temperature storage of hydrogen requires materials with high strength, stiffness and toughness in extremely low-temperature hydrogen-rich environments. Consideration of existing and new materials suitable for such applications is a key element for designing and delivering hydrogen storage infrastructure.

Understanding of requirements

While there are significant potential opportunities offered by hydrogen, there is also uncertainty in what future demands and requirements are likely to be. Greater understanding of the 'pull' in terms of future use-cases is required in order to help identify where investment in future research is likely to be most fruitful.

Development of novel materials and coatings

Investment in novel materials, coatings and chemical mitigations which potentially overcome the degradation challenges posed by hydrogen should be explored. Coatings may be particularly applicable for retrofitting existing assets (such as gas compressors).

2.3.2.2 Operate and maintain

Mitigation of hydrogen degradation effects

Mitigating the degradation effects of hydrogen is a significant engineering challenge. While there is no single solution to this challenge, appropriate material selection along with the application of coating systems (when required), are important aspects.

Integrity assessment

Design and structural integrity assessment codes and methods are a key enabler for industry in delivering hydrogen infrastructure, particularly for components running at extremes of temperature and stress for significant periods of time (such as those in gas turbines and compressors). While experience from existing assessment codes is likely to be invaluable, further work is required to develop and agree appropriate codes and methods to assess material degradation in hydrogen environments. Furthermore, dissemination and training of practitioners in such approaches is a vital part of their effective use by industry.

Development of standards and personnel

There is currently a lack of awareness of which standards are most appropriate for assessment of components in hydrogen environments. As a result, collaboration and investment is required to:

- Develop and agree standards appropriate for assessment of components in hydrogen environments
- Disseminate and promote understanding of these standards throughout relevant industries.

2.3.2.3 Decommission and disposal

As hydrogen and its related technologies are still emerging, specific requirements for decommissioning and disposal are not fully understood.

2.3.2.4 Fundamental understanding

Characterisation and understanding of degradation mechanisms

There are knowledge gaps concerning degradation mechanisms such as hydrogen embrittlement, including understanding and modelling of long term effects of hydrogen environments upon structural materials and the interactions with other damage mechanisms. This presents opportunities for researchers to resolve at the multi-centre, industry-led level; this is likely to require significant support by funding bodies to bring to fruition.

In contrast, polymer materials (such as fibre-reinforced composites) are not subject to the same embrittlement issues affecting steels, and could enable cost reduction along with safer, more reliable delivery of hydrogen. However, before widespread industry acceptance of these materials, significant research and testing is required to understand the behaviour and degradation mechanisms of such materials in a hydrogen environment.

The parallel roadmap, 'Materials for end-to-end hydrogen' [26], aligns well with the findings of this report in that the structural degradation challenges it identifies are also found in the degradation pathways for high volume compressors, the repurposing of existing pipelines infrastructure, and materials for liquid hydrogen storage.

Material testing

For some applications, there are barriers to access testing data and test facilities for the compatibility of existing metals and alloys in hydrogen and ammonia environments, which could delay the adoption and/or approval for use. As such, there are infrastructure gaps which need addressing to forge new collaborations in undertaking long term testing and sharing materials test data in hydrogen environments across applications and industries.

Two key areas of testing have been identified by stakeholders as playing a vital role in understanding and de-risking the degradation challenges posed by hydrogen environments:

- Long-term testing programmes for existing engineering materials in representative hydrogen environment; to support repurposing of existing assets and components
- Testing of hydrogen effects upon non-metals, particularly polymers and fibre-reinforced composites.

In order to support the delivery of these, long-term, collaborative research and testing programmes are required, potentially supported by the development of full scale hydrogen test facilities.

Coordinated action

Collaboration between policymakers, academia and industry is required to understand and clarify which hydrogen technologies are most important in achieving net zero, to allow the relevant material degradation challenges to be prioritised.

2.4 Carbon capture and storage (CCS)

2.4.1 Context and introduction

CCS is an emergent technology which offers the potential to decarbonise sectors that inherently produce carbon such as steel production, existing natural gas power generation and blue hydrogen generation.

Industrial processes such as the synthesis of aviation fuels or enhanced oil extraction can use the captured CO_2. In addition to the re-use of captured CO_2, current CCS plans aim to store captured CO_2 safely in geological features such as depleted gas reservoirs, however this requires additional studies and development.

CCS is strategically identified in point 8 of the UK government's 10 Point Plan for a Green Industrial Revolution [8], in addition to being a key international strategy and technology for decarbonisation [27]. However, whilst a potentially critical technology for decarbonising some industries, CCS as a technology is still in its infancy. Hence, there remain substantial technical challenges lacking understanding and experience in many areas such as the sealing and capping of CCS injection wells, and long term CCS degradation of polymers.

Many materials degradation challenges exist with similar themes to hydrogen, although noting that the important mechanisms are distinctly different.
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2.4.2 Opportunities and challenges

2.4.2.1 Design and manufacture

Learning from existing projects and demonstrators

As CCS is an important technology for decarbonising parts of industry, there are several international projects and demonstrators being trialled [28] [29]. There is an opportunity to learn from these activities to inform where future research tasks need to focus.

Repurposing existing infrastructure

In order to scale up CCS operations, the repurposing of existing infrastructure (e.g. pipelines and distribution networks) is required for CO_2 transportation. This requires a detailed and more fundamental understanding of CO_2 interaction with non-metallic materials, with particular focus on long term durability and permeation.

2.4.2.2 Operate and maintain

Life prediction methods

Methods for appropriate life assessment of CCS facilities don't currently exist, establishing these is fundamental for the safe operation of CCS facilities whilst maximising their operational life. Developing these also requires a fundamental understanding of the degradation mechanisms and challenges presented by CO_2 environments.

2.4.2.3 Decommission and disposal

As carbon capture and storage and its related technologies are an emergent technology, specific requirements for decommissioning and disposal are not fully understood. However, these will share similarities with some current oil and gas infrastructure.

Long term storage of CO_2

There is a need for consideration of the long term carbon storage and sequestration implications on the carbon cycle, and possibility of leakage and the release of stored CO_2 into the atmosphere and deep ocean [30].

2.4.2.4 Fundamental understanding

CO_2 interactions with materials used in existing infrastructure

In relation to understanding how the use of existing infrastructure with CO_2 affects materials degradation, the exercise identified the following research areas:

- Corrosion, carburisation, and related threats in capturing CO_2 from hot flue gases and transportation of dense phase CO_2
- Corrosion, scaling, carburisation, and cracking of steel pipelines, in wet, dense phase CO_2 environments, and development of predictive models, monitoring and inspection technologies
- Understanding CO_2 interaction with non-metallic materials; long term durability, permeation
- Stability of wellbore cementing on exposure to supercritical CO_2 which could prevent the reuse of existing oil/gas wells for sequestration
- Fracture in CO_2 pipelines: some work has been done but clear guidance and standards acceptable to regulators is needed.

CO_2 interactions with non-metallic materials

There are still large gaps in knowledge concerning degradation mechanisms of polymer materials in real life situations which is required to make accurate component life predictions.

Key challenges include:

- Quantifying the durability of polymers in long-term contact with supercritical CO_2 for use as seals for pressurised equipment, and
- Understanding the ageing and micro damage of composites exposed to hostile fluids.

These present a great opportunity for academia/industry project(s) to resolve at the multi-PhD, industry-led level requiring government support and influence to bring to fruition.

Well capping and concretes in long term CO_2

Use of cements and concretes in capping wells, where service lives of thousands of years are required with no loss of effective performance, involves potentially significant challenges which are critical to achieving long term safe storage of CO_2, and requires substantial support and investment.

2.5 Transport

2.5.1 Context and introduction

Four key areas of transport have been considered in this exercise; these are:

- Aerospace
- Rail
- Road
- Sea/marine.

Material degradation challenges are well documented in the transportation sector, a recent example being the Class 800 series Hitachi trains, where a fatigue issue meant that over 150 trains had to be taken out of operation due to safety concerns. This fatigue issue was estimated to cost between £1m and £2m a day, and caused considerable disruption to services [31].

Degradation issues in the aerospace sector are also responsible for costly disruptions and grounding of aircraft due to safety concerns. A recent example is the emergency airworthiness directive on the Pratt & Whitney PW4000 engine, due to fan blade fatigue cracking issues [32].

For highly safety critical applications such as aircraft, transparency of issues and the measures taken to address them is essential, as not doing so can result in significant risk to human life, and tragedy. An example of where diligent inspections and transparency resulted in the safe identification and rectification of a turbine blade durability issue, regardless of the cost, is the Rolls-Royce Trent 1000 engine. In total this issue has been estimated to cost in the region of £2.4 billion between 2017-2023 [33].

Whilst the reduction of carbon emissions from road transportation is an important aspect in achieving net zero 2050 [10], its suitability for electrification and the high (TRL) of electric vehicle technologies means that few issues were identified in this sector. Structural batteries are a potentially promising technology for reducing the weight of electric vehicles, however this report does not cover these technologies, as they are in the early stages of R&D.

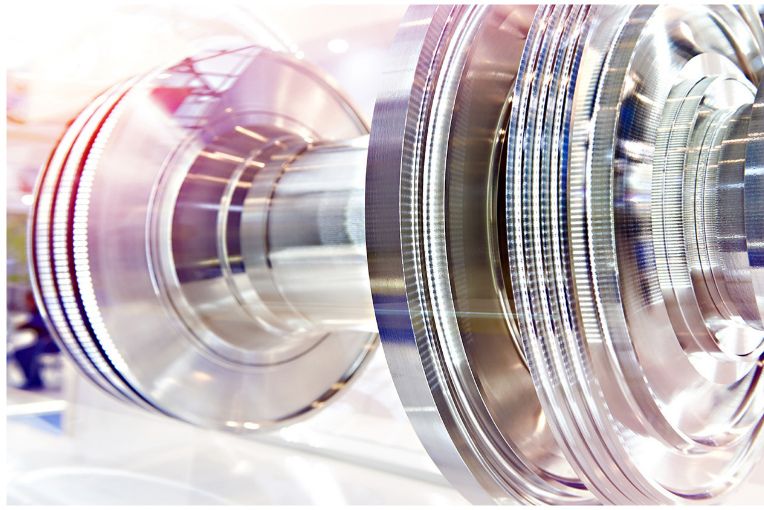
Similarly, rail is already a highly electrified sector within the UK and does not produce significant carbon emissions beyond those associated with electrical power generation [10]. Therefore, many of the responses on transport focused on the challenges and opportunities present in the aerospace and marine sectors. In comparison, electrification is less suitable for long haul aircraft applications and freight transport due to the low energy density, high cost and limited operational life of batteries.

> ***"Promising alternative fuels for the marine and shipping industry are ammonia and hydrogen, as they are zero carbon."***

Flyzero presented a useful insight into the possible application of some of the aerospace propulsion technologies available for the decarbonisation of the sector in March 2021 [34], this insight is also supported by the Rolls-Royce: Leading the Transition to Net Zero Carbon report [35]. Flyzero identified that long-haul (1500 – 7500 nautical mile range) twin aisle aircraft will likely be heavily dependent on developments to gas turbines (GTs) to use sustainable (bio derivative) and synthetic (carbon-neutral fuels synthesised from captured carbon) for the foreseeable future.

Single aisle aircraft and regional (1000 – 1500 nautical mile range) aircraft will similarly rely on sustainable and synthetic fuelling of GTs in the near term (next 15 years) but offer the possibility of utilising combined hydrogen fuelled GTs or fuel cells with electrification in the longer term.

The new and fast developing electric vertical take-off and landing (eVTOL) vehicle sector opens up a new opportunities for sub-regional aircraft with a high TRL.



In relation to propulsion systems for aerospace, this section focuses on existing technologies, namely GTs, and the decarbonisation and reduction of carbon emissions of these technologies. Reductions in the carbon emissions of GTs can be achieved through improved design, and adaptations to use sustainable and synthetic fuels.

Promising alternative fuels for the marine and shipping industry are ammonia and hydrogen, as they are zero carbon, can be used with existing technologies, offer good energy density, and can be produced sustainably with renewables and nuclear. However, a definitive strategy on the most suitable technologies for decarbonisation is still required for both aerospace and marine, making it difficult to prioritise research opportunities in this sector.

2.5.2 Opportunities and challenges

2.5.2.1 Design and manufacture

Use of composites for weight reduction

Fibre-reinforced composites offer a great opportunity to improve the fuel-efficiency and performance of many transportation vehicles through weight reduction and corrosion resistance. While their use is widespread in the aerospace and rail sectors, opportunities still exist to broaden their usage across the transport sector.

Development of higher temperature composites

Contributors to this exercise identified a requirement for the development of higher temperature composites for use in GTs and other power generation applications. These materials could include ceramic matrix composites and carbon/carbon composites, but further R&D and performance testing is required to develop these materials for existing applications.

Advanced manufacturing

Advanced manufacturing techniques such as electron beam welding, and AM give rise to opportunities for rapid, automated, manufacture of components with more complex geometries, and faster prototyping of components.

Courtesy of TWI Ltd

This facilitates design optimisation of components. The use of advanced manufacturing techniques may also facilitate better-optimised component designs which help reduce material degradation and extend the life of the component or system. However, research and development into advanced manufacturing techniques, design, testing and certification standards could allow more widespread use of these methods for more components and applications and hence allow for greater industry adoption.

> *“Consideration of the lifecycle implications of material selection will improve both the longevity and sustainability of components.”*

Alloy casting techniques

Through optimising and improving the casting methods and tooling design used to manufacture components, there is potential to improve the fatigue and corrosion performance of cast components by reducing or even eliminating defects, impurities and inclusions.

Material selection and development

Consideration of the lifecycle implications of material selection will improve both the longevity and sustainability of components. For example, cheaper alloys with lower refractory element content and poor corrosion resistance are commonly used in transport and infrastructure applications, where a more corrosion-resistant material would offer longer life and improve overall sustainability.

2.5.2.2 Operate and maintain

Life assessment methods for composites

The exercise identified a need for the development of standards to predict through-life performance and repair of composites. In particular, there are a lack of rigorous standards which account for the degradation resulting from the absorption of liquids, high cycle fatigue (HCF), fracture, UV damage and creep. In a similar vein, while many composites can be repaired, the inspection and validation of the quality of repairs is an evolving area ripe for greater focus. Improved understanding in both these areas would support and accelerate the application of composites.

Machine learning to support inspection and life assessment

Inspection supported by image recognition/correlation methods is a valuable research area in relation to life extension of transport assets and infrastructure.

Machine learning (ML) techniques have the potential to augment human identification of material degradation/damage, potentially allowing faster and more comprehensive inspection of structures. Efforts with particular focus upon aerospace applications are ongoing [36] [37]; however, such methods could have a significant cross-sectoral relevance.

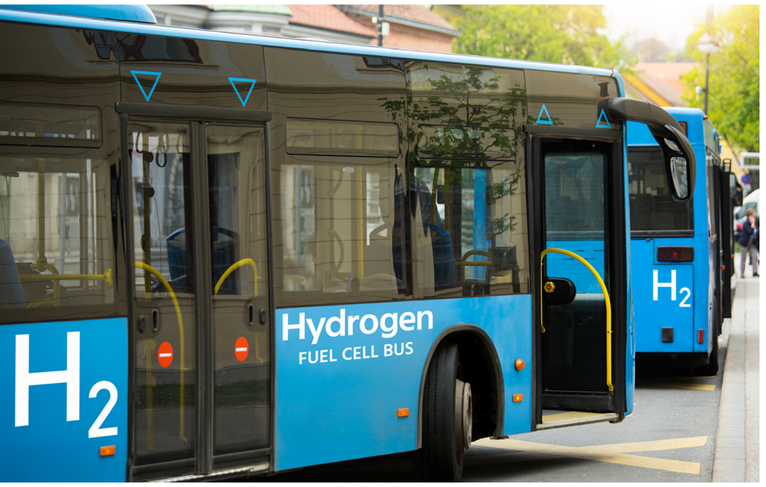
Infrastructure and concrete

Across all the four transport areas, there is an opportunity to reduce the environmental impact and emissions associated with infrastructure, through extending the life of concretes and reinforced concrete.

Stainless steel reinforced concrete has improved longevity compared with standard reinforced concrete and is increasingly used. However, there is a lack of understanding on how to best protect and therefore maximise the return from many stainless steel reinforced concrete applications.

Use of hydrogen and ammonia as a fuel

Research into hydrogen's use within transportation is required to enable its utilisation as a fuel. With respect to structural materials, such required research consists of creep, corrosion-fatigue and creep-fatigue testing in hydrogen and ammonia environments. Affected systems are applications, fuel delivery systems and power generation systems such as GTs and reciprocating engines.



> *The recyclability of materials has a direct impact upon sustainability and emissions related to transport assets and infrastructure.*

Inspection and monitoring

Further development of inspection and monitoring techniques such as ultrasound, eddy current and thermography can help to maximise the safe usage from components or assets. The inspection and monitoring process tie in closely with damage tolerance and life assessment methods.

Microbial corrosion in marine environments

Microbial corrosion is a challenge for metals in aqueous or moist environments, some of the key issues which need research and development include:

- Improved risk assessment, prediction, and modelling (e.g., where, when, and why does biofilm form)
- Elucidation of coupled microbial metabolisms and potential novel bio-markers
- Improved detection and monitoring (e.g., deployable, accurate, sensitive biofilm/corrosion sensors)
- Improved concepts to prevent biofilm formation (e.g., new materials/surfaces/coatings to disrupt biofilm life-cycle dynamics).

2.5.2.3 Decommission and disposal

Recyclability of materials

The recyclability of materials has a direct impact upon sustainability and emissions related to transport assets and infrastructure; addressing recyclability has an indirect impact upon degradation of the materials.

Composites are particularly difficult to recycle and have a significant environmental impact; thermoplastic composites offer improved recyclability and are suitable for some lower strength applications such as covers, cowlings and bodywork.

The recycling of metallic alloys is also an important consideration for sustainability. This was highlighted as a potential area where significant reductions in CO_2 can be realised through improvements in "scrap sorting and separation" and "recycling-oriented alloy design" [6].

2.5.2.4 Fundamental understanding

High temperature materials for gas turbines

GTs offer high power density for transport applications and as such are widely used in aerospace. They can also support a range of biofuels and can run on hydrogen and ammonia. By increasing the operational temperatures of the turbine there is the opportunity to develop more efficient GTs, which can utilise lower carbon fuels. As such, increasing operational temperatures has always been a focus in GT development.

However, there are a number of structural material degradation challenges limiting performance in this area:

- GT materials are able to perform in extreme high temperature environments with the use of protective high temperature thermal barrier coatings. These coatings degrade and breakdown over their operational life and as such, more research into coating methods and techniques can help increase turbine efficiency and lifecycle
- Improved mechanistic understanding and life assessment methods for creep, creep-fatigue, and stress assisted corrosion and corrosion-fatigue through a holistic approach to characterisation (not investigating the mechanisms in isolation to each other). In so doing, developing a robust methodology to appropriately determine the life of components in-service and the mitigation processes needed for a particular environment or application
- Understanding of material performance in environments relevant to future fuels, such as hydrogen.

For high temperature materials, the UKs capabilities in microscopy, characterisation and in situ microscopy present an opportunity to conduct innovative research. This research is fundamental and will help progress our materials and materials degradation understanding in high temperature applications.

Concrete production

Concrete production is reported as contributing to 8% of global anthropogenic CO_2 emissions [38]. Therefore, significant reductions in CO_2 can be made through research into lower carbon alternatives to cement and concrete, and the decarbonisation of concrete production.

> *For high temperature materials, the UKs capabilities in microscopy, characterisation and in situ microscopy presents an opportunity to conduct innovative research.*

Long-term testing programmes

Long-term testing programmes are required to ensure safe reliable operation, with respect to some degradation mechanisms such as high cycle fatigue, and long term exposure to harsh environments. Relying on extrapolations from accelerated test data can be difficult and can lead to inaccurate models, and the requirement for unnecessary inspection activities.

3

Exploitation of potential cross-sector synergies

Based on the sectoral review described in the previous section, six common cross-sectoral themes have been identified as described below.

These are the key areas identified for investment which will result in cross sector benefits.

1. Design and manufacture
2. Modelling and simulation
3. Maintenance and inspection
4. Characterisation and testing
5. Knowledge and data management
6. Leadership and policy.

These areas align well with findings from the Henry Royce Institutes materials 4.0 over-arching executive summary [39], which makes the core recommendation of the establishment of a 'National Steering Group for Digital Materials & Manufacturing' to examine the current state of digital materials science.

3.1 Design and manufacture

For improved sustainability across the lifecycle of assets, consideration of material degradation is equally as crucial at the design and manufacturing stages as it is throughout the operational life. Several general considerations and areas for work were raised by in the exercise in relation to this.

Material selection and surface treatments

Effective materials selection can reduce and mitigate the effect of degradation; this can also be supplemented through careful consideration of manufacturing processes. As an example, surface treatments such as coatings can offer improved degradation performance, which leads to improved longevity and reduced environmental impact of components.

Utilising material degradation mitigation techniques while at the design stage can offer lifecycle optimisation and improvements in sustainability. These techniques can be overlooked or ignored as a result of the ignorance around the environmental impact of a throwaway culture.

Development of new materials systems

The development of new materials and alloy compositions can lead to improvements in the materials performance in terms of manufacturability, durability and recyclability all of which contribute to increased sustainability.

Material development requires R&D and characterisation facilities to work alongside manufacturing in order to develop materials with good manufacturability. The UK is well placed for materials research capability (for example through the recent large investment in the Royce institute); however, manufacturing and casting is often performed overseas or by a separate company or supplier to the one designing the component, meaning international collaboration is often required to conduct successful research in this area.

Coatings and protection

Through the use and development of coatings and protection techniques such as cathodic protection, degradation of material systems can be limited and slowed, extending their operational life. The following possible research areas with a cross-sector relevance were raised by the exercise:

- Extending the use of cathodic protection on reinforced concrete infrastructure
- Developing coating systems for protection against hydrogen environments
- Developing coating systems to prevent biofilm formation and bio corrosion.

The development of novel coatings requires R&D and characterisation facilities to work collaboratively with manufacturing engineers in order to develop coatings with good manufacturability.

> ***"Through the use and development of coatings and protection techniques such as cathodic protection, degradation of material systems can be limited and slowed, extending their operational life."***

Advanced manufacturing

Advanced manufacturing techniques such as additive manufacturing, electron-beam melting and laser machine welding enable quick prototyping and the manufacture of components with complex and optimised geometrical design. Optimised component geometry can help to reduce weight while offering improved cooling and improved function. In order to utilise AM for in-service components, design codes, guidance and standards are needed on the manufacture, and certification of components.

3.2 Modelling and simulation

Modelling and simulation methods provide mathematical representations of real-world systems, in order to provide the answer (or answers) to a pertinent question (or questions). It is generally accepted that modelling and simulation plays a key role within materials science and mechanical engineering, for design optimisation, developing fundamental understanding and for predicting the behaviour of engineering systems.

Cross-sectoral themes have been identified in two broad categories, namely:

- Mechanistic models, which are based upon understanding of physical or mathematical principles which underpin the behaviour of the modelled system
- Empirical models (or phenomenological models), which are based upon data from the modelled system, rather than a mechanistic understanding of the system.

In addition, due to the increasing number and sophistication of modelling and simulation techniques, integration of simulation techniques and modelling and simulation infrastructure are of increasing importance for solving complex materials degradation problems, as outlined below.

Mechanistic models

Mechanistic modelling of materials is an increasingly important tool for understanding and predicting degradation behaviours at different length-scales (from atomistic to continuum scales) and comprises a wide range of approaches.

A detailed review of mechanistic modelling approaches is beyond the remit of this report, but such techniques include continuum mechanics (e.g., Finite Element Analysis), fracture mechanics, crystal plasticity, dislocation dynamics and molecular/atomistic dynamics.

A recent road mapping effort on multiscale mechanistic modelling [34] outlines a number of key challenges. A key recurring theme is the need for continued investment and coordination of research and development of a wide spectrum of mechanistic modelling methods and software.

Furthermore, to achieve continued adoption of novel mechanistic modelling approaches by industry, ongoing engagement between academia and industry is required to disseminate greater understanding of use-cases and limitations of the range of potential approaches.

Empirical models

Empirical modelling spans techniques from the relatively simple (such as linear regression models) through to the cutting-edge (such as deep learning methods). Some techniques have a long history of application to materials degradation problems, whereas others are in their infancy. In particular, recent advances in machine learning have had a significant impact upon the modern world but are relatively immature as applied to materials degradation problems.

Expertise in many of these empirical modelling techniques lies with a range of disciplines which have traditionally sat at a distance from materials sciences, including statisticians, data scientists, and machine learning experts. This expertise should be leveraged to identify and explore opportunities for future innovation through, greater dialogue with and collaboration between these experts and domain experts in materials sciences.

Integration of simulation techniques

There is a growing desire for improved integration of different simulation techniques, driven by requirements for multiscale and multiphysics modelling as well as better integration with data sources (e.g. sensor data, materials test data).

To enable this, ongoing development and cross-disciplinary collaboration is needed to allow different modelling methods and software to interface with each other (to allow for easier integration).

Modelling and simulation infrastructure

Increasingly sophisticated simulation and modelling approaches are being used to investigate various aspects of materials degradation behaviour. These approached are made possible by modern computation infrastructure, comprising high-performance computing resources, simulation software and data and connected experimental facilities, as outlined by [39].

Such infrastructure requires continuous development and investment to understand and meet the needs of users across academia and industry. Dedicated programmes to drive such efforts (such as those being led by the Hartree Centre) are likely to play a key role in ensuring the UK's modelling and simulation infrastructure remains competitive.

3.3 Maintenance and inspection

The safe operational life and productivity of assets and systems can be optimised through maintenance procedures and inspection methods. The exercise identified several gaps in which targeted research is required to support the maintenance and life extension of assets.

Inspection techniques and life extension

In many sectors there is a need for improved inspection methods, techniques, and equipment as well as guidance documentation and standards. These inspection standards and processes need to be supported by methods to determine ongoing safe operation, inspection intervals and routines. For composite materials in particular, improved guidance on inspection techniques and processes, would support an increased uptake in the usage of these materials.

> ***"The safe operational life and productivity of assets and systems can be optimised through maintenance procedures and inspection methods."***

There are also opportunities to use modelling methods to inform and guide predictive maintenance tools. Sectors such as aerospace and nuclear have built up experience in this area, presenting opportunities for collaboration to widen the use of existing modelling approaches to new applications.

Research programmes which explore the application of new and improved inspection techniques are required for a range of metallic and non-metallic materials; these research efforts should be undertaken in collaboration with inspection equipment manufacturers and end users.

Repair and material joining

In combination with inspection and life extension methods is the requirement for material joining and repair techniques. The re-inspection of repairs is also a crucial element for certification, feeding back into the requirement for new and improved inspection techniques. The repair of materials that are difficult to recycle (such as composites) can offer opportunities for improved sustainability. However, whilst carbon fibre and composites are repairable, there is a need for standards and guidance on how to repair and certify repairs in this sector. Research into material joining and repair often requires modelling and experimentation, which is research well suited to UK facilities.

3.4 Characterisation and testing

Characterisation covers a spectrum of activities in the structural materials degradation space. Here it refers to material testing and the generation of degradation performance data and understanding. This is required for assurance, to provide data to inform life assessment models, and to develop understanding of degradation mechanisms, all of which underpins the management of materials degradation and related activities.

Combined mechanisms of degradation and environmentally assisted degradation mechanisms

The exercise raised a growing need to better understand the material degradation mechanisms acting in combination, and within the environment in which the material is required to operate. Often fatigue, creep or corrosion testing is conducted in isolation, however combinations of mechanisms can interact and in many cases the significance of their interaction needs better understanding. The respondents highlighted this in relation to hydrogen and CO_2 environments, as well as higher temperature operation.

The combined degradation mechanisms highlighted by the exercise as needing further exploration and study were:

- Aqueous corrosion-fatigue and SCC
- Creep-fatigue
- High temperature corrosion/oxidation and fatigue
- Stress assisted corrosion and oxidation mechanisms
- Environmentally assisted creep crack growth.

Specialist testing equipment with environmental chambers is often needed to perform such testing. There is the need to consider (and potentially improve) the availability of such equipment and facilities to support testing within hydrogen, CO_2, high temperature and aqueous environments.

Long term test programmes

It was identified that longer term testing programmes are often expensive and difficult to run within the confines of a normal research projects for the following reasons:

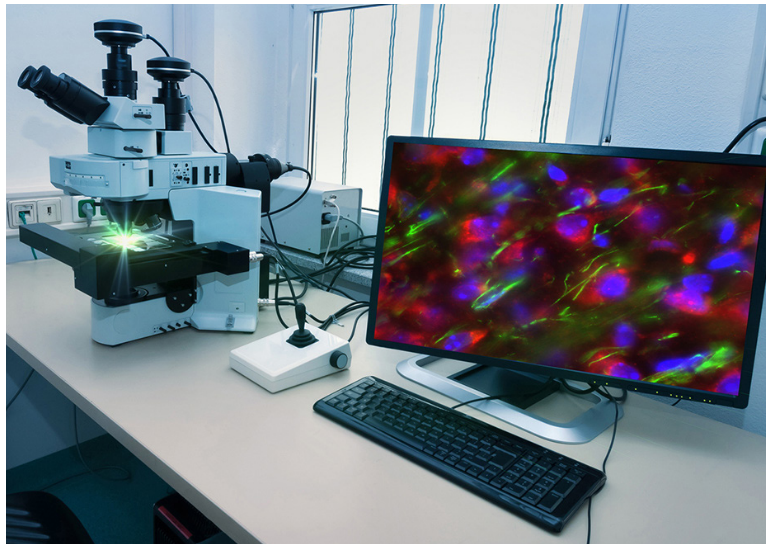
- Postdoctoral projects commonly last only 1-2 years (3 years max.), and fellowships 5 years; subsequently, expertise is often lost over time, making longer research programmes difficult to fund
- Limitations on capital expenditure often constrains investment in longer research programmes, making such programmes difficult to fund from either the private or public sector.

Such testing programmes are important for applications which require long term integrity. This was highlighted as an issue for CCS well caps, nuclear waste storage facilities and polymer seals within carbon environments. However the challenges of performing long term testing, or of applying accelerated test data to longer term life predictions exists across all the sectors.

Funding these long term test programmes, such as those required for CCS well caps and nuclear storage facilities needs clear strategic leadership to provide confidence in the technologies, and recognise the importance of these types of test programmes to achieving the target of net zero 2050.

In-situ imaging and experimentation

To better understand the fundamental mechanisms behind material degradation, microscopy imaging and characterisation is required alongside material testing programmes. This can use a range of imaging techniques such as SEM, TEM, XRD and synchrotron/high energy x-rays.



The exercise identified that to further progress our understanding of degradation mechanisms, there is a need to perform these imaging techniques *in-situ* with experimental testing. These activities are needed to underpin the life assessment strategies and management of material degradation.This requires collaborative research programmes and effort to ensure industrially relevant questions are addressed.

The UK has some world-leading facilities to support situ imaging and experimentation, such as Diamond light source and the UK's National Research Facility for X-ray Computed Tomography (NXCT). Future academic and industrial research programmes should continue to capitalize on expertise and equipment offered by these facilities.

3.5 Knowledge and data management

Knowledge and data management was raised by the respondents as a challenge which can limit the effectiveness and benefit realised from materials degradation research. Holistic consideration of sharing and management of both data and knowledge is required between industry and academia. The following cross-sector topics were identified by the exercise in relation to knowledge and data management.

Expertise and training

For many of the technologies required to realise net zero 2050, a new generation of technical and industrial experts is required. Training these new experts presents opportunities to leverage existing experience across sectors. An example raised by the exercise was the opportunity to utilise oil and gas experience to support CCS and offshore wind. This experience ranges across design, manufacture, operation, maintenance and decommissioning activities.

In order to effectively organise training and knowledge sharing programmes, suitable topics need to be identified where relevant expertise and knowledge exists. Funding is required to promote and support these cross sector training programmes.

Design codes, standards and guidance

Consistently across the respondents, the need for standards and guidance on the manufacture and use of materials were identified in a number of areas; cross-sector areas are listed below:

- Standards for the use of stainless steel reinforced concrete, and utilising cathodic protection of concrete
- Standards for the assessment of components in hydrogen environments
- Standards for the repair, and certification of repairs in composites
- Standards for manufacture, testing and certification of advanced manufactured components.

Some stakeholders have noted that there are no Government funding support schemes for industry professionals to join standards committees, which often makes it difficult for senior and knowledgeable people to participate in standardisation activities. It was also identified that in some cases there is the opportunity to streamline standards committees through supporting focused management and direction. Efforts to address these issues would help with more effective development and dissemination of standards.

Management of intellectual property

Materials degradation data and findings often have cross-sector uses; however commercial requirements to protect intellectual property present significant hurdles in publishing and discussing these with the wider community and industry.

Initiatives and projects which aim to encourage cross-sector collaboration are a good way to promote constructive sharing of intellectual property.

3.6 Leadership and policy

The exercise identified overarching cross-sector opportunities, challenges, and synergies which were organisational in nature. These require consideration on a strategic and leadership level.

Funding

Currently funding bids require a novel element to be successful. However, research proposals related to some aspects of materials degradation, such as steel and concrete, may not always be seen as especially novel but are nonetheless an important part of meeting long-term net zero goals. It is without doubt that common engineering and manufacturing materials will continue to be used far more frequently than novel materials to ensure new infrastructure can be delivered over the coming decades. Making better use of existing materials, in combination with implementing more informed mitigation strategies, is of no less importance than developing novel materials. Leadership and strategy development is required to explore funding approaches for projects and initiatives which address material degradation and operational challenges with both existing and novel methods.

Realising new and emergent technologies

Supporting new and emergent technologies through from concept to production is critical both to support the UK to develop itself as a green energy leader, and to achieve net zero. Catapult centres are a good way to address this, through fostering collaboration, but only if they have top level strategic direction and guidance to ensure a common goal.

A potential way to successfully foster collaboration and focused output driven research is a national challenge programme such as the Faraday Battery Challenge [40]. This is a good example of a programme and funding strategy which focuses on an end deliverable goal, of the commercialisation of battery technologies for electric vehicles.

Programmes like this provide an incentive for collaboration and problem solving. Similar approaches could be adopted to address the opportunities and challenges identified above, through programmes for training and sharing of expertise and developing new methodologies or techniques.

4

Conclusions

In order to achieve the ambitious target of net zero by 2050, transformative change and decisive action is needed.

Across the materials and wider engineering and scientific community, there is a strong resolve to address the issues presented by this transition. There is unanimous recognition of the importance of structural material degradation to achieving the target. Furthermore, there are numerous cross-sector opportunities for UK industry and academia to help address these challenges and realise new export opportunities.

The project identified six cross-sector areas where systematic work is required to address these challenges, namely:

- Design and manufacture
- Modelling and simulation
- Maintenance and inspection
- Characterisation and testing
- Knowledge and data management
- Leadership and policy.

Meeting these challenges within these areas in a focussed, efficient, and effective manner requires high-level direction and strategic leadership. The vaccine rollout in response to the COVID-19 pandemic has shown that senior leadership can be instrumental in breaking down barriers to progress. In a similar vein, senior leadership providing clear direction is likely to be key in setting the direction of travel in overcoming the challenges in achieving net zero.

The identification of a need for high-level direction and strategic leadership is a conclusion mirrored by a recent statement from the Science Academies of the Group of Seven (G7) nations [41]. This statement recommends that every government should 'develop an evidence-based roadmap setting out the technologies that it requires to achieve the goal of reducing greenhouse gas (GHG) emissions to net zero'. Additionally, this conclusion is reinforced by recent plans announced by the UK Prime Minister to establish a new National Science and Technology Council [42].

Collaboration is required between governing bodies, industry, and academia; doing so effectively requires promotion and encouragement through focused initiatives, communicated from a leadership position.

There is also a need for clarity and coordination on the technologies and strategies to focus on in order to deliver net zero. In many sectors there are a wide range of technologies often in competition with one another as the greenest solution. To provide both investment confidence and sense of purpose for the research community, a holistic, clearly communicated strategy to achieve net zero is required. For such a strategy to have the authority and credibility required, it is imperative that it should be developed as a collaborative effort between senior policymakers along with a broad range of cross-sectoral academic and industrial stakeholders. It is proposed that a technology roadmap could be a good method to communicate this strategy to the materials and materials degradation community by identifying key technologies and delivery dates to help guide investment decisions and inform strategic R&D activities.

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Annex A

Survey questions

Please identify the key strategic opportunities which are imperative to delivering net zero 2050 in your sector.

1. What opportunities are there (current and/or future) for achieving net zero 2050 in your sector?

2. In relation to the opportunities you have identified above, please define the structural material degradation challenges which are impeding our progress, or could act to impede our progress towards net zero. Focus on how these challenges present an obstacle towards realising the higher level opportunities.

Research priorities

In light of your answers in the previous section, please identify your top five structural material degradation research priorities in order of importance to your industry/sector in achieving net zero 2050 (a minimum of two is required).

1. What is the first material degradation research priority?

2. Which materials are affected by this challenge?

3. What research is required to address this challenge, and how will this help in achieving net zero 2050?

4. Rank the importance of this challenge to achieving net zero 2050 for the UK.

UK exploitation

In this section, please identify the top five technologies and capabilities in which you think UK investment could help to exploit the research and development priorities you identified on the previous page (a minimum of two is required).

1. What is the first technology or capability which can be used to address structural material degradation challenges in your sector?

2. Rate the UKs capability to perform research in this area, from 1: poor capability to 5: good capability.

3. Rate the UKs readiness to develop and commercialise this capability or technology, from 1: poorly positioned to 5: well positioned.

Please comment on which institutions and research companies are leading on structural material degradation issues relating to your sector. Please include departments or business units where possible.

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