

Position Paper on
Engineering Structural Integrity:
A Vital Enabler for Net-Zero
Part 2: Full Paper

Forum for Engineering Structural Integrity
Henry Royce Institute for Advanced Materials

Contents

Executive summary

Glossary

Forward

Appendices **1**

Appendices **1**

1 Importance of Engineering Structural Integrity to the UK **1**

2 ESI technologies for the UK to reach Net-zero **2**

3 Technological opportunities for ESI **4**

4 Research and innovation landscape **5**

5 Roles and competency in ESI **7**

6 Addressing the skills shortage **8**

7 Testing facilities **9**

8 International research collaboration **10**

9 Codes and standards and regulatory development **10**

10 Regulatory frameworks **10**

11 Leadership and a National Strategy for ESI **11**

12 Conclusions **12**

13 Recommendations **12**

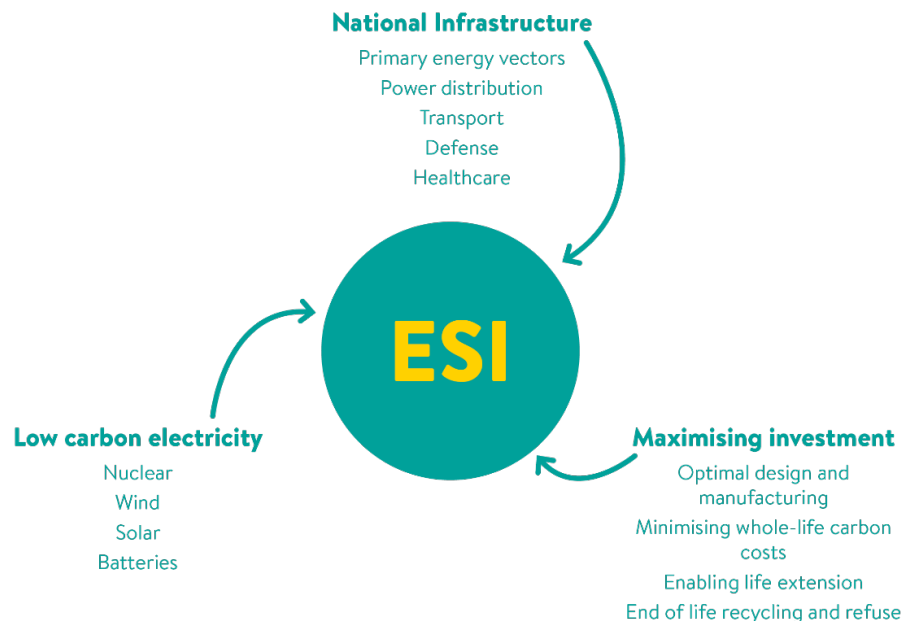
14 Acknowledgements **12**

15 References **12**

Appendices

Executive Summary

The UK's economy, security, well-being and prosperity depend on safe, enduring and resilient infrastructure to deliver our energy, defence, transportation, and healthcare. The total value of critical UK infrastructure and the cost of replacement runs into trillions of pounds. Engineering structural integrity (ESI) is the integrated multi-disciplinary set of activities spanning science and engineering that ensures the operational integrity of that critical UK infrastructure; in parallel, it underwrites life extension of our major assets, providing the UK with huge economic and societal benefits and environmental protection.



This Position Paper, commissioned by the Henry Royce Institute for Advanced Materials (Royce) and prepared with the UK Forum for Engineering Structural Integrity (FESI), summarises the criticality of ESI to the UK economy and the opportunities afforded through a nationally co-ordinated approach to ESI technology, research, and training. It is allied to the [National Materials Innovation Strategy](#), which has identified structural integrity and the performance of materials in service as a key cross-cutting theme.

The Opportunity

ESI is a key underpinning UK resource that is central to the growth of the UK economy. The UK's journey to Net-zero depends on ESI skills, methods and activities for reducing whole-life carbon costs and maintaining a sovereign capability for safe operations and readiness. ESI activities seek to minimise the impacts of ageing and maximise the life of our vital existing infrastructure to increase the return on investment.

Significant investment in future infrastructure for the UK to achieve Net-zero highlighted by the National Infrastructure Commission – modular nuclear reactors, floating offshore wind turbines, a hydrogen storage and distribution network, and carbon dioxide sequestration – will require innovation to advance ESI methods before any new infrastructure can be deployed and gain regulatory consent. Data mining and machine learning for design, probabilistic prediction of in-service performance, and real-time data reduction from extensive monitoring and diagnostics all represent major opportunities for greater efficiency and economies and which could be deployed at pace to huge benefit.

The Challenge

Since the turn of the millennium, ESI in the UK has become fragmented across diverse organisations and industrial sectors with decreasing innovation and connectivity. The UK's ESI skills base is under threat from a rapid reduction in the number of new graduates and professional engineers, scientists and technicians entering and active in the field. Failure to invest sufficiently in ESI can result in the high financial and human costs of over-engineering, catastrophic failures, breakdowns, lengthy and costly repairs and downtime.

Proposed Key Interventions

ESI is a “hidden discipline”, as it is often only considered when things go wrong; however, it is critical upfront to efficient and safe design of new infrastructure as well as to sustaining in-service reliability assurance. Therefore, for the UK to achieve its Net-zero objectives the UK must:

- **Grow its ESI Community** and focus on ESI training and professional development with urgency to ensure a competent and skilled workforce.
- **Assess and rationalise access to appropriate ESI** testing and experimental capabilities
- **Boost its international presence** so it can benefit from knowledge exchange and technology transfer from other advanced economies.
- **Develop more efficient regulation of innovation in ESI** in order to enable faster introduction of novel approaches and the benefits they will bring.

Recommended Next Steps

To deliver on this, the ESI Community in the UK must establish clear leadership, direction, and integration to drive innovation, transfer technologies, develop skills and share knowledge and experience between industry sectors.

To meet the challenges outlined above requires the formation of a new *industry-led Umbrella Organisation for ESI*, with a government-convened public-private *Leadership Group* representing the whole ESI community. The Group will set out the future requirements and drive the implementation of a coherent *UK National Strategy for ESI* with input and endorsement from key stakeholders in industry, government, universities, research and technology organisations and regulators. It will form part of the **National Materials Innovation Strategy**. Outputs will be:

- Production and dissemination of a *UK National Strategy for ESI*.
- Mechanisms and forums to *coordinate our distributed capabilities* around the UK, to make judicious investment decisions in high priority areas, and to ensure that we develop the necessary capabilities to support our industry/infrastructure.
- Development of an evolving *Roadmap for ESI* to focus and accelerate ESI innovation in areas such as data science, AI and advanced diagnostics.
- An audit of skills training and professional development across the range of ESI disciplines specifying the requirement for a *UK ESI Training and Skills Academy*.
- Assessment of needs for *capital investment in ESI testing facilities* for Net-zero infrastructure while ensuring that existing national facilities are utilised efficiently.
- *Improved dissemination of knowledge and new methods* across disciplines and industry sectors, linking the many organisations whose activities relate to ESI.

The key recommendations are that the ESI Community should by the end of 2024 or soon after:

- **Establish an Umbrella Organisation and Leadership Group** that will implement an overarching UK National Strategy for ESI so that the UK can meet its Net-zero aims.
- **Engage with National Funders, including the Research Councils and Innovate UK** and with the key industry sectors, to ensure the financial sustainability of the underpinning facilities and skills delivery for ESI.
- **Establish the framework for a UK National ESI Training and Skills Academy** for different ESI disciplines in line with the ESI Roadmap.

Investment in engineering structural integrity is vital for the UK economy, generating the knowledge, skills and infrastructure to deliver the UK's commitment to Net-zero.

This report has been prepared by a small Project Team and received input from an Advisory Group representing the ESI community. It is now issued as a "Draft for Comment" by the wider ESI community before it is officially launched and disseminated to government and other bodies.

Key Industrial Sectors

Energy, defence, transport, space, civil infrastructure and the build environment, medical devices.

Key Stakeholders

Universities, Research and Technology Organisations, Consultancies, Aerospace Technology Institute, The British Institute of Non-Destructive Testing (BiNDT), UK Institutions of Structural Engineers, Civil Engineers; Mechanical Engineers, Institute of Materials, Minerals and Mining (IOM3).

Glossary of terms and acronyms

AGR	Advanced Gas-cooled Reactor
AFRC	Advanced Forming Research Centre
AI	Artificial intelligence
AMR	Advanced Modular Reactor
AMRC	Advanced Materials Research Centre
BINT	British Institute for Non-destructive Testing
DRA	Defence Research Agency
EA	Environment Agency
EIS	Engineering Integrity Society
EEMUA	Engineering Equipment and Materials Users Association
ESI	Engineering Structural Integrity
ESIS	European Structural Integrity Society
FESI	Forum for Engineering Structural Integrity
HOIS	Harwell Offshore Inspection Service
HSE	Health and Safety Executive
HTGR	High Temperature Gas-cooled Reactor
IMechE	Institution of Mechanical Engineers
ICChemE	Institution of Chemical Engineers
ICE	Institution of Civil Engineers
IoM3	Institution of Materials Minerals and Mining
MOD	Ministry of Defence
MTC	Manufacturing Technology Centre
NCC	National Composites Centre
NDA	Nuclear Decommissioning Authority
NDT	Non- Destructive Testing
NNL	National Nuclear Laboratory
NPL	National Physical Laboratory
NSIRC	National Structural Integrity Research Centre
ONR	Office for Nuclear Regulation
ORR	Office for Road and Rail
ORE	Offshore Renewable Energy (Catapult)
PWR	Pressurised Water Reactor
RCNDE	Research Centre for Non-Destructive Examination
RTO	Research and Technology Organisation
SMR	Small Modular Reactor
SQEP	Suitably Qualified and Experienced Person
UKAEA	United Kingdom Atomic Energy Authority
UKRI	United Kingdom Research and Investment

Forward

This Position Paper was commissioned by the Henry Royce Institute for Advanced Materials under the UK Forum for Engineering Structural Integrity (FESI). The overall vision is for strategy to secure the key role that ESI needs to play for the UK to achieve its Net-zero carbon emission objectives.

Engineering structural integrity (ESI) is the integrated multi-disciplinary set of activities spanning science and engineering that ensures the *operational integrity* of that critical UK infrastructure; in parallel, it underwrites *life extension* of our major assets, providing the UK with huge economic, societal and environmental benefits.

This Position Paper, commissioned by the Henry Royce Institute for Advanced Materials (Royce) and prepared with the UK Forum for Engineering Structural Integrity (FESI), summarises the criticality of ESI to the UK economy and the opportunities afforded through a nationally co-ordinated approach to ESI technology, research, and training. It is allied to the [National Materials Innovation Strategy, which](#) has identified prediction of materials performance/degradation as a key cross-cutting theme. It aims to assist in formulating UK government policy and identifying and channelling funding routes towards initiatives, facilities, and research in ESI, and working with research and technology organisations, academia, and key industry sectors and regulators.

There are major opportunities for exploiting advances in materials, computing power, big data, artificial intelligence and machine learning, and remote sensors to develop new approaches that will reduce the whole-life cost of constructing, operating and managing the structures and facilities on which the country depends.

The Position Paper applies to a broad section of industry sectors focusing on those where there is a direct contribution to achieving our Net-zero objectives, such as offshore wind, nuclear power, hydrogen pipelines and carbon dioxide sequestration. In addition, it is relevant to manufacturing, aerospace, defence, transportation and the bio-medical field. All these sectors can significantly contribute to achieving the UK's Net-zero objectives.

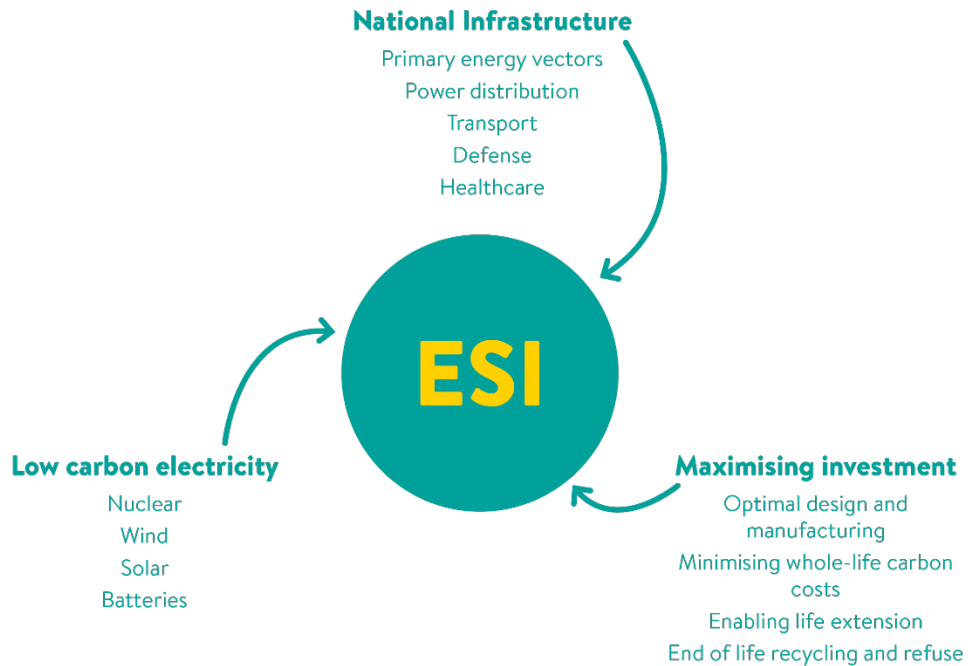
All relevant aspects of ESI are considered within the scope of the Paper. These include such aspects as inspection, non-destructive examination (NDE), and condition monitoring, degradation processes such as corrosion, fatigue, creep and strain ageing, manufacturing, and joining methods, stress analysis, defect tolerance and issues relating to data collection, storage and application. The range of relevant materials considered spans metals, composites, cementitious materials and polymers.

The Paper addresses the challenges for ESI through the life of a structure or component, from achieving efficient optimised design and defect free manufacturing to in-service assessments of ageing and degradation. It has not been the purpose of this paper to provide significant information on reuse, re-purposing, decommissioning and waste storage although these aspects are undoubtedly important and have their own ESI issues. The emerging role of future modelling and experimentation requirements is considered as is the whole issue of skills requirements and associated training and development.

This report has been prepared by a small project team chaired by Professor Mike Fitzpatrick and representing FESI and the Henry Royce Institute for Advanced Materials. It has been drafted primarily by Professor John Wintle of TWI Ltd and the University of Strathclyde with input and guidance of an expert Advisory Committee representing the different parts of the ESI community. It is now issued as a "Draft for Comment" by the wider ESI community before it is officially launched and disseminated to government, UKRI and Innovate UK, and other bodies.

1 Importance of Engineering Structural Integrity to the UK

The UK's economy, security, well-being and prosperity depend on safe, enduring and resilient **infrastructure** to deliver our energy, defence, transportation, and healthcare. The total value of critical UK infrastructure and the cost of replacement is vast running into **£tn. Engineering structural integrity (ESI)** is the integrated multi-disciplinary set of activities spanning science and engineering that ensures the operational integrity of that critical UK infrastructure while underwriting life extension of our major assets thereby providing the UK with huge economic and societal benefits and environmental protection [1].



This Position Paper, commissioned by the Henry Royce Institute for Advanced Materials (Royce) and prepared with the UK Forum for Engineering Structural Integrity (FESI), summarises the criticality of ESI to the UK economy and the opportunities afforded through a nationally co-ordinated approach to ESI technology, research, and training. It is allied to the [National Materials Innovation Strategy, which](#) has identified structural integrity and the performance of materials in service as a key cross-cutting theme.

ESI is a key underpinning UK resource that is central to the growth of the UK economy. The UK's journey to Net-zero depends on ESI skills, methods and activities for reducing whole-life carbon costs and maintaining a sovereign capability for safe-operations and readiness. ESI activities seek to minimise the impacts of ageing and safely extend the life of our extensive existing infrastructure to increase the return on investment and defer the cost and inconvenience of replacement.



Structural integrity innovation has enabled the UK's nuclear reactor fleet to generate twice as much green electricity than their original design, delivering major reductions in CO² emissions and economic benefits. The ability to extend the operation one Power station at Hartlepool provides 3% of the UK's electricity needs! The Advanced Gas-cooled Reactor (AGR) stations and Sizewell B Power Station have saved 1.4 billion tonnes of CO² emissions, and their operation is underwritten by structural integrity

The importance of ESI is not widely recognised – that is until a critical piece of infrastructure, plant, or equipment fails or is out-of-service. The cost of failures to individuals, government, and the whole UK economy is huge, particularly when public safety is compromised. Failure to invest sufficiently in ESI can have a huge impact on the UK resulting in high financial costs of over-engineering, unforeseen catastrophic failures, breakdowns, lengthy and costly repairs and down-time.

In 2021 metal fatigue cracks found on a large percentage of our train services resulted in mass withdrawal of service for four weeks. Structural integrity assessment and non-destructive testing were essential to getting this fleet back up and running, delivering huge economic benefit, while ensuring passenger safety as repairs took place.



Since the millennium, ESI in the UK has become gradually **fragmented** across diverse organisations and industrial sectors with decreasing innovation and connectivity. The UK's **ESI skills base is under threat** from a rapid reduction in the number of new graduates and professional engineers, scientists and technicians entering and active in the field. This is at a time when there is massive opportunity to deploy the advances in ESI technologies, computing and information management to realise greater efficiency and economies and which could be deployed at pace to huge benefit

2 ESI technologies for the UK to reach Net-zero

For the UK to reach its Net-zero objectives will require both the construction of major new infrastructure and life extension of existing plant and equipment to defer the financial and carbon cost of replacement. The National Infrastructure Assessment (Appendix 1) identified *four areas of new infrastructure that will be required for the UK to reach Net zero by 2050* [2]:

- Offshore wind,
- Modular and large-scale nuclear reactors (PWR, SMR, HTGR, AMR),
- Hydrogen production, storage and pipeline network,
- Carbon dioxide capture, transportation and sequestration.

The significant investment in future infrastructure highlighted by the National Infrastructure Commission will require innovation to advance ESI methods before any infrastructure can be deployed and gain regulatory consent: data mining and machine learning for design, probabilistic prediction of in-service performance, real-time data reduction from extensive monitoring and diagnostics all represent opportunities which could be deployed at pace to huge benefit.

ESI technologies will be a key enabler to solve the many different engineering challenges to achieve Net-zero [3] (see Appendices 2-5). They will require sustained research and development before government and other large-scale investors can make a substantive policy and financial commitment. Regulators will need to assess the evidence necessary to validate the use of new technologies before they can be approved. New manufacturing processes and procedures will need to be qualified, tested, and standardised before they can be accepted.

Net-zero will also require an economy that is more energy efficient and using less material and resources than today. ESI technologies can make new infrastructure more energy efficient and carbon neutral through enabling designs that are lighter and stronger, using less material and by employing advanced manufacturing methods to enable quicker and more cost-effective construction [4]. In addition to the four specific areas of new infrastructure above, there are

many other areas of engineering where new approaches to ESI would lead to significant economic benefits as well as reducing carbon emissions:

- Lightweight transportation including automotive and rail
- Nuclear fusion reactors
- Low carbon propulsion systems
- Rockets, spacecraft, and satellites
- Advanced more rapid defect-free manufacturing processes
- Durable and long-lasting medical devices
- Defence equipment, weapons and facilities
- Concrete-light civil structures in the built environment

New approaches and methods in ESI exploiting the emerging technological opportunities will apply through the life of engineering assets (Fig 1) facilitating:

- Advanced new designs, materials and manufacturing methods
- Operational integrity and safety
- Addressing uncertainties about ageing/degradation that are limiting asset life
- Optimised in-service inspection regimes and fitness-for-service assessment
- Safe life extension for assets to be operated for longer before replacement.

ESI is also relevant at later stages of plant and equipment life where reuse, recycling, repurposing, mothballing, decommissioning, recycling or waste storage can be envisaged. While the Paper does not deal specifically with these aspects, ESI can play a role in ensuring existing infrastructure is sustainably managed. There will be opportunity to reuse and repurpose some redundant infrastructure where ESI can show the integrity is compatible with the new duty.

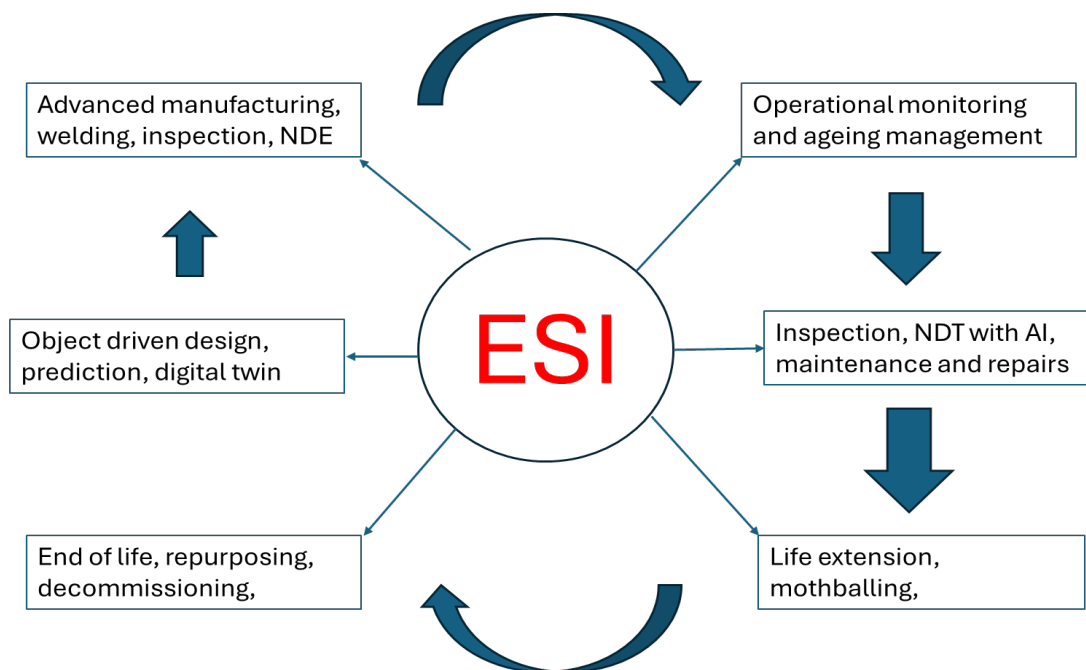


Fig 1 Role of ESI through the life of engineering assets

ESI technologies are essential for the supporting the infrastructure required to reach Net-zero and the cost of failing to invest sufficiently could be very high. The energy and defence sectors are areas where failures of components and equipment can significantly impact the UK's strategic interests. For example, the UK's submarine nuclear reactors and aircraft carriers have had serious structural integrity issues where ESI was essential to keeping them at sea [4]. The early generation of offshore wind turbines will be reaching their design life within a few years and ESI will be needed to make the case for life extension.

3 Technological opportunities for ESI

The timescales to Net-zero do not allow the luxury of expansive R&D programmes and work must be completed in a much shorter time. Fortunately, the UK is not starting from scratch. Advances in computing and intelligent software are enabling the solution of problems much faster than was previously possible.

The advent of immense computing power and storage means that data on materials, design and manufacturing, coupled with the ability through artificial intelligence to recognise patterns and trends in operating and inspection data, is creating opportunities for the development of new data-led approaches in ESI.

Engagement of ESI practitioners with the data science and machine learning community offers the possibility of object-driven design and manufacturing [5, 6]. The ability to run complex structural models many millions of times with iterations of input variables is likely to enable design and manufacturing specifications to be determined to optimise end cost, reduce material usage, and/or extend the expected service life. Retrieving, capturing, storing and repackaging the data that exists from testing and operational experience will provide the source learning for artificially intelligent systems.

Historically, materials performance was largely determined empirically through extensive programmes of materials testing and in-service surveillance. Studies are on-going aimed at the ability to model materials at a microstructural compositional level and to predict their macroscopic properties and behaviour within an engineering structure [7]. These numerical models can be across a wide range of length scales and incorporate multi-physics processes that reflect material changes over time.

Multi-physics and multi-scale damage modelling and numerical analysis will have the potential to substantially reduce the amount and cost of experimental testing required to validate a new material or manufacturing process. For example, modelling could predict the performance of materials in extreme environments such as ultra-high or -low temperatures or under exposure to environmental conditions such as strong radiation fields or corrosive environments. Nuclear fusion needs rare materials that can only be tested in tiny amounts, so the challenges of fusing limited test data and high-fidelity models are compelling.

New manufacturing and joining processes will bring products to completion more quickly but will require qualification to ensure long-term performance. Processes such as additive manufacturing can reduce the amount of material and energy used in fabrication, as well as the number of joints in a structure which are often the weakest part. New methods of welding such as electron beam and friction stir will find applications for the rapid construction of wind turbine towers. Surface engineering technology is already improving the longevity of artificial hip joints.

For the UK to meet its Net-zero objectives, much greater understanding will be required of the processes that degrade structures and components under the range of environmental conditions for which there is no complete knowledge. These can have a profound effect on the material structure and properties. They include the formation of defects from welding and additive manufacturing, hydrogen embrittlement and cracking of high strength steel, carbon dioxide corrosion of pipelines, fatigue, high-temperature creep and strain ageing.

Improved modelling of materials performance that can predict the rate of degradations will allow more targeted intervention. Better prediction and models of degradation and ageing processes will need to be complemented by some testing, inspection and condition monitoring because the assumptions made about operating environments are not always correct. The assurance provided by

design codes diminishes with time and more emphasis on in-service data and assessment becomes necessary, particularly as operating conditions can change.

Testing of representative structures will still be needed to validate the models and provide assurance for unaccounted mechanisms and factors. Advances in sensors and wireless communications will enable the behaviour and condition of components to be known in real time so that changes can be detected at a much earlier stage. The key challenges are detecting indications of degradation with less or no human intervention using long range and remote NDE technologies and doing so in increasingly complex geometries and harsh environments.

We need to simultaneously enhance detection modalities for early confirmation of degradation mechanisms, and develop the analytics to detect, characterise, diagnose, and predict the time to failure so timely responses can be initiated. These technologies will ultimately replace how the integrity of structures and components is currently managed and reduce the need for human intervention. The application of big data sets and advanced trending and insights using artificial intelligence (AI) algorithms will provide better tools for predicting degradation. Probabilistic methods will enable the assessment of fitness-for-service and risk from defective or damaged components to be made with greater resolution.

Allied to materials modelling and intense structural monitoring lies the creation of a detailed digital twin of the structure. The twin will model the design and manufacture as implemented and will be updated as the structure is operated under the relevant loading and environment using data-centric methods based on through life data collection, storage and damage assessment. This is already in place for aircraft fuselage frames and engines and is providing greater resolution of damage hot spots in real time allowing increased operating cycles.

4 Research and innovation landscape

Historically, the UK had world-class centres for research and technology development for almost every industrial sector. The Central Electricity Generating Board and British Gas had their own extensive research laboratories. Nuclear research was undertaken by the UK Atomic Energy Authority and British Nuclear Fuels Limited, and railways research at the British Rail Technical Centre. There was also a cohort of universities undertaking research on ESI themes in areas such as pressure systems, high-temperature components, materials plasticity, fatigue and fracture. Many of these organisations have substantially changed or no longer provide the focus for research they once did. Many university materials departments have been subsumed into larger broad engineering schools.

Research and innovation in ESI technologies is still being undertaken at UK universities, research and technology organisations (RTOs) and national research centres but at a lower volume and more fragmented than was historically the case. Some larger companies, engineering consultancies and verification bodies are major users of ESI technologies and undertake their own development work. The engineering institutions (e.g. the Institution of Mechanical Engineers) and networks such as FESI and the Engineering Integrity Society are platforms for seminars and conferences in ESI and some are also providers of training courses.

A (non-exhaustive) list of some examples of the important UK organisations involved in ESI is shown in the Table below. (See glossary for a list of acronyms)

Universities	RTOs	Consultancy Verification bodies	Technology Transfer Training and guidance	Companies Regulators
Oxford	TWI	Frazer Nash	FESI	Rolls-Royce
Manchester	UKAEA	Atkins	EIS	MOD
Bristol	NTC	Amentum	ESIS	BAe Systems
UWE	NAMRC	RINA	IMechE	EdF Energy
Coventry	NNL	Penspen	ICChemE	SSE
Cranfield	NPL	COWI	ICE	SP
Leicester	NCC	Lloyd's Register	IoM3	EoN
Nottingham	ORE	Allianz	BINT	RWE
Sheffield	MTC	HSB	RCNDE	NDA
Birmingham	AFRC	DNV GL	Hazards Forum	Sellafield
Brunel	HOIS	BV	Energy Institute	ONR
Imperial College	Qinetiq	TUV (ABB)	EMMUA	HSE
Southampton	DRA		Welding Institute	ORR
Bangor	UK Space Agency			EA
Strathclyde				

The UK government research agency, **Innovate UK**, provides funding for projects in which ESI is involved. Building a secure and resilient world is one of its strategic themes, but it does not explicitly recognise ESI as one of its major topics [8]. There is a need to ensure that UKRI through Innovate UK, EPSRC and STFC acknowledges the importance of ESI for the UK and highlights it within its calls for proposals.

Research and Technology Organisations (RTOs) undertake early-stage research and near market development as well as addressing specific operational problems of industry within their competencies but tend to operate competitively rather than collaboratively. Some of these organisations have advanced experimental facilities and equipment for ESI testing whose cost would be difficult to justify elsewhere. They are active in the development of early-career technologists and also fill a need for training in specific skills for technicians in activities including welding, non-destructive examination, and materials testing. RTOs have the capacity and knowledge of ESI to co-ordinate activities across industry and academia, and across different disciplines and industry sectors.

In terms of **technology transfer and training**, there are many UK organisations offering publications, conferences, seminars and training courses on ESI topics. However, because they are competing for the same or overlapping markets they do not communicate, co-ordinate or co-operate as effectively as they could.

The conclusion is reached that ESI research and technology, development and dissemination is fragmented within the UK and requires leadership, direction and innovation if the UK is to maintain sovereign control of its critical infrastructure and facilities. There is a need for greater communication and co-operation between organisations within an agreed national strategy for ESI, supported by government and funding agencies and industrial policy. There is a need to invest in the ESI research base where there are significant opportunities for technological advances to realise societal and economic benefits.

5 Roles and competency in ESI

The activities of ESI encompass many different trained and skilled scientific and engineering professionals in disciplines in the roles shown below.

Engineering Structural Integrity Disciplines			
Mechanical Engineering	Materials Science & Chemistry	Engineering and Physics	Physics and mathematics
Design	Materials properties & behaviour	Plant operations & performance	Inspection and monitoring
Stress analysis	Manufacturing, welding and joining	Thermal hydraulics and heat transfer	Condition data gathering
Failure and fitness-for-service analysis	Ageing & degradation, corrosion, fatigue embrittlement, creep	Environmental loads, transient and accident conditions	Non-destructive testing – close and remote
Safety and remaining life assessments	Surface engineering treatments, coatings and claddings	External events, impact and seismic loadings	Data analysis and analytics, trending, probability of failure
Codes, standards, procedures and industry guidance			
Safety case development and regulatory requirements			

Those filling professional roles in ESI will possess academic qualifications, knowledge in mathematics, physics or chemistry and those in professional roles will mainly have a first degree in science or engineering and often PhD research experience. Their training and associated professional development will usually be obtained from industrial roles or post-doctoral research.

ESI is also dependent on the technical personnel needed for welding, non-destructive testing, manufacturing, materials testing and sample preparation. These roles require a good level of technical education combined with practical skills and the ability to develop and follow procedures.

The foundation and qualifications of professional and technical roles in ESI are defined by the requirements of the relevant professional engineering institutions. There are also recognised standards and qualifications for personnel to undertake welding and non-destructive testing. However, the competencies required for specific ESI roles (e.g. structural modellers) are not as well established.

The assessment of whether a structure or plant is fit-for-purpose and can safely operate is usually a demanding and senior role within an organisation. It requires significant levels of engineering experience to make decisions on engineering integrity and safety that can have far-reaching consequences. These roles need a high standard of communication and other non-technical skills to interface effectively with management, regulators, and other stakeholders.

There is now a new focus on the development of Non-Technical Skills for engineers which have been shown to be crucial for safety in other sectors. These include situational awareness, decision-making, communications, judgment, leadership and teamworking. A fast track for high-calibre engineers to develop these skills for ESI decisions should be a matter of priority for universities and companies to fill the senior roles needing competencies in these areas.

The delivery of ESI needs the supply of suitably qualified and experienced personnel (SQEP) for the different roles. Organisations make their own judgments about the competency and professionalism of an individual, and some companies are now setting their own competency requirements for different roles. In general, however, the concept of SQEP in ESI needs to be much more widely recognised across industry to ensure that those undertaking work with a high impact to public safety are sufficiently qualified and competent.

6 Addressing the skills shortage

Historically, UK industries, universities, national laboratories and research institutes have invested in training, competency and skills of engineers and scientists for ESI roles. *However, a rapid reduction in recent years in the number of skilled and experienced people entering and active in the ESI field has placed the UK's scientific and engineering capability and skills base in ESI under threat.* At every level there is a reported shortage of people wishing to enter ESI roles and many university and industrial places remain unfilled. This is due to:

- Reduced support for the National Structural Integrity Research Centre (NSIRC), which in the last ten years has enabled over 400 students to complete research degrees.
- Reduction in the number of University Centres for Doctoral Training aligned to ESI, due to the cross-sector role of ESI spanning different disciplines.
- Shortages of people enrolling, qualifying and pursuing roles integral to ESI, from technical skills in welding and non-destructive testing, through to more advanced analytical and engineering management roles.
- Insufficient recognition of the roles and career opportunities of ESI in schools and at undergraduate level, and of its importance to the UK by government bodies, research funding agencies and some industrial companies.

In practice, ESI is an exciting career choice covering a huge range of sectors and skills, with opportunities to address challenges around the globe, under the ocean and into space. It offers prospects to have a critical role in the engineering design, manufacture and operations for the future, working across disciplines, embracing data and reaching into everything from offshore wind turbines to medical devices. There are diverse roles to suit both the more academic and the practical person.

The ESI practitioner is usually found working in a team, linking practice to experiments and numerical methods, using data-centric approaches, and drawing on sensor data from the real-time environment to manage something like a major power plant, plane or rocket. They often interact with system designers and operators, regulatory authorities, and be called as expert witnesses when things go wrong. They keep the lights on and wheels of the economy safely turning.

ESI has made good progress in attracting more female applicants but there is still a large pool of talent untapped. ESI should be promoted as offering a career with strong societal impact and a level of flexibility not found in other fields. It also employs many applicants from more diverse ethnic backgrounds and could attract more qualified personnel from overseas by changes in requirements for visas.

Those from these communities have generally proved to be a great asset to their respective companies or universities.

The government-supported **UK National Structural Integrity Research Centre** (NSIRC) has enabled over 400 PhD students to complete MSc and PhD research degrees on ESI topics under the joint supervision of technologists and academics from TWI, industry and UK universities [9]. NSIRC has now reached the end of its planned 10-year duration. There is therefore an urgent need to refresh national ESI research priorities across a wider range of organisations in a way that meets the requirements of UK industry and Net-zero objectives.

To meet its Net-zero objectives aims, the UK needs to place greater focus on **ESI training and professional development** and sustaining ESI skills and research base. There would be considerable benefit from having a more joined-up approach through which research, skills training and personnel development could be better co-ordinated. Such a vision needs to be part of an over-arching UK National Strategy for ESI.

7 Testing facilities

The UK has traditionally had some of the best and most unique facilities for ESI testing. These facilities were built to address public and regulatory concerns to provide unique experimental data against which models and predictions could be judged. Examples from the nuclear sector include the research reactors at Harwell and the facilities at Risley to demonstrate the integrity of nuclear pressure vessels. The safety of UK North Sea oil and gas tubular jacket structures and pipelines was underpinned by the test rigs at TWI and the National Engineering Laboratory determining their fatigue life and enabling life extension.

While many UK testing facilities associated with ESI have reached the end of their useful life, the UK still has major test facilities for specific purposes:

- HSE Science Division facilities for accident investigation, impact and crash testing
- DNV facilities at Spadeadam for explosion tests on structures
- Facilities at TWI for testing hydrogen damage, sour service, fatigue and fracture including a pressure pit and resonance fatigue testing of pipelines.
- Facilities run by Amentum at the Birchwood site for tests under pressurised water reactor conditions and on graphite and nuclear materials at high temperatures.
- The Inspection Validation Centre at the Amentum Birchwood site
- Hot cells at Sellafield for tests on irradiated material
- Equipment at many UK universities including the Henry Royce Institute
- The ISIS neutron source and Diamond Synchrotron X-ray Source at Harwell for investigations into material microstructures and residual stress [10]

The challenges for the UK to reach Net-zero are likely to require investment in further testing facilities. Consequently, a review should be made of where the UK will need new facilities and other experimental capabilities. These will include equipment for testing structures such as floating offshore wind turbines, components for small and high temperature modular reactors, the properties of steel and other materials exposed to liquid and gaseous hydrogen and the performance of existing pipelines exposed to carbon dioxide at high pressure.

8 International research collaboration

In the past the UK has been a leader of international research collaboration in ESI projects. For example, the Network for Evaluating Structural Components (NESC) in the nuclear industry was a collaboration addressing issues of nuclear safety of PWR power plants in which the UK played a key role. The UK ESI community needs to have continued international influence on behalf of UK plc. It needs to invest in co-ordinated UK engagement with international networks so that the UK can benefit from knowledge exchange, technology transfer and access to facilities from other advanced economies.

This engagement should, for example, take the form of greater participation in European Horizon Projects, international standards committees and sending delegations to key conferences and meetings. Engagement with US, South Korean and Japanese research is also important where significant advances are being made. *There would be benefit in having greater co-ordination between organisations with a common interest so that the costs and information from attending international meetings can be shared within the UK community.* The UK government has an important role in facilitating these exchanges.

9 Codes and standards and regulatory development

The designs and construction of safety critical structures are governed by industry regulators and qualification bodies, statutory regulations and the requirements of recognised codes and standards. Examples include nuclear plant, pressure systems and offshore wind turbines where national and international standards complement guidance produced by industrial bodies and engineering institutions.

The introduction of new technology therefore must be in conjunction with these organisations with sufficient evidence and experience provided such that the technology can become standardised. There are established routes for standardisation, but the processes for building up sufficient evidence and experience for acceptance can be very slow.

The R5 and R6 procedures for high temperature creep and defect tolerance procedures are state-of-the-art and can be construed as a UK flagship used widely around the world. However, their future development under the co-ordination of EDF Energy is in doubt as the AGR fleet approaches end of life.

The UK requires codes and standards bodies to adopt a more vigorous approach to standardising new engineering designs, materials, manufacturing and joining methods, and procedures for assessing fitness-for-service. Research and technology organisations should be encouraged to produce guidance and recommended practices where these would be advantageous.

10 Regulatory frameworks

The ownership and operation of engineering critical structures with a safety or societal function in the UK are often subject to a regulatory regime. Examples of structures regulated in the way are nuclear installations and licensed sites (the Office for Nuclear Regulation), pressure systems and equipment (the Health and Safety Executive), gas transmission lines (OfGen) and medical devices (MHRS). New engineering structures and components and technologies will need to overcome regulatory hurdles.

Regulators such as the HSE previously had significant safety related research programmes and provided a platform for UK to learn from the experiences of other countries. These programmes have reduced during the last twenty years to a point where regulators are relying on operators to produce all the necessary evidence in support of safety.

Fortunately, *the UK's regulatory framework is based on ownership of risk under a goal setting regime and regulators adopt a positive attitude to innovation.* The Office for Nuclear Regulation, for example, has a Strategy for Innovation which advocates early engagement with industry proposing to use new technologies in safety cases, a process known as sand-boxing [11].

In fulfilment of their responsibilities and avoiding the danger of relying too much on interested parties, regulators should have access to more independent advice and expertise in approving new technologies. The Boeing 737Max has been a timely and salutary lesson in the requirement for robust, competent and independent regulation.

11 Leadership and a National Strategy for ESI

ESI is critical upfront to efficient and safe design of new facilities for Net-zero as well as to sustaining in-service reliability assurance of existing infrastructure. Therefore, for the UK to achieve its Net-zero objectives the UK must:

- **Grow its ESI Community** and focus on ESI training and professional development with urgency to ensure a competent and skilled workforce.
- **Assess and rationalise access to appropriate ESI** testing and experimental capabilities
- **Boost its international presence** so it can benefit from knowledge exchange and technology transfer from other advanced economies.
- **Develop more efficient regulation of innovation in ESI** in order to enable faster introduction of novel approaches and the benefits they will bring.

To deliver on this, the ESI Community in the UK must establish clear leadership, direction, and integration to drive innovation, transfer technologies, develop skills and share knowledge and experience between industry sectors.

To meet the challenges outlined above requires the formation of a new industry-led *Umbrella Organisation* for ESI, with a government-convened public-private *Leadership Group* representing the whole ESI Community. The Group will set out the future requirements and drive the implementation of a coherent *UK National Strategy for ESI* with input and endorsement from key stakeholders in industry, government, universities, research and technology organisations and regulators. It will form part of the *National Materials Innovation Strategy*. Outputs will be:

- Production and dissemination of **a UK National Strategy for ESI**.
- **Mechanisms and forums to coordinate our distributed capabilities** around the UK, to make judicious investment decisions in high priority areas, and to ensure that we develop the necessary capabilities in the UK to support our industry/infrastructure.
- Development of an evolving **Roadmap for ESI** to focus and accelerate ESI innovation in areas such as data science, AI and advanced diagnostics.
- An audit of **skills training and professional development** across the range of ESI disciplines specifying the requirement for a **UK ESI Training and Skills Academy**.
- Assessment of needs for **capital investment in ESI testing facilities** for Net-zero infrastructure while ensuring that existing national facilities are utilised efficiently.
- **Improved dissemination of knowledge and new methods** across disciplines and industry sectors, linking the many organisations whose activities relate to ESI.

12 Conclusions

The principal conclusions from this Position Paper are as follows.

- ESI is a key UK resource and enabler for achieving the UK's Net-zero objectives ensuring that the critical infrastructure on which the UK relies are cost effective, reliable, and enduring and that the new facilities the UK requires can be constructed more efficiently and economically.
- ESI research and technology development is fragmented across many organisations and requires greater leadership, direction, integration, and innovation for the UK to retain control of critical infrastructure and facilities.
- The volume of research and number of people working in the ESI field needs to be increased to exploit the major opportunities for technological advances.
- ESI in the UK urgently requires clearer leadership, direction, and integration to drive innovation, transfer technologies, and share knowledge and experience.

13 Recommendations

From these conclusions, the key recommendations are that the ESI community should by the end of 2024 or soon after:

- **Establish an Umbrella Organisation and Leadership Group** that will develop an overarching **UK National Strategy for ESI** so that the UK can achieve its Net-zero objectives.
- **Engage with National Funders**, including the Research Councils and Innovate UK and with the key industry sectors, to ensure the financial sustainability of the underpinning facilities and skills delivery for ESI.
- **Establish the framework for a UK National ESI Training and Skills Academy** for different ESI disciplines in line with the ESI Roadmap.

14 Acknowledgements

The Project Team of Professor John Wintle, Professor Peter Flewitt (now deceased), Professor Mike Fitzpatrick, Professor David Knowles and John Sharples would like to thank the Members of the Advisory Committee and others who have made individual contributions (listed in Appendices 6 and 7) for their valuable support.

15 References

1. Flewitt PEJ and Dowling AR, The development of structural integrity assessment methods, An overview. Methods for the assessment of structural integrity of components and structures, Published by Maney for IMMM, ISBN 1-892653-78-5, 2003.
2. National Infrastructure Commission, National Infrastructure Assessment, October 2023
3. Editorial, Structural integrity in the context of carbon neutrality, Special issue, Fatigue and Fracture of Engineering Materials and Structures, Wiley, October 2023
4. Defence Nuclear Enterprise, Delivering the UK's Nuclear Deterrent as a National Endeavour, [Delivering the UK's Nuclear Deterrent as a National Endeavour \(publishing.service.gov.uk\)](https://publishing.service.gov.uk), ISBN 978-1-5286-4782-3, 2024.
5. UK Government, Pro-innovation of technologies review – Advanced manufacturing, November 2003.

6. Feng Y, Zhao Y, Data-driven product design toward intelligent manufacturing: a review, Int J Advanced Robotic Systems, March 2020
7. Martínez-Pañeda E, Computational predictions of weld structural integrity in hydrogen transport pipelines, Int J of Hydrogen Energy, Available on-line, 25 January 2024.
8. UK Research and Investment, Strategic Theme: Building a secure and resilient world, December 2023
9. Lloyds Register Foundation, Foresight review of structural integrity and systems performance, LR Foundation report series: No 2015.1, October 2015.
- 10.** Diamond light source, <https://www.diamond.ac.uk/Science/Integrated-facilities/active-materials-laboratory.html>
11. Office for Nuclear Regulation, [ONR's approach to regulating innovation](#), Updated March 2024.
12. James et al, UK Programme on codes and standards and procedure needs for SMR and Gen IV reactors, Proc ASME PVP 2018-85075, 2018.
13. James et al, UK Programme on codes and standards and procedure needs for SMR and Gen IV reactors – Phase 1 output, Proc ASME PVP 2019-93861, 2019

Appendix 1

The National Infrastructure Assessment for Net-Zero

In its Second National Infrastructure Assessment, the National Infrastructure Commission takes a 30-year view of the infrastructure needs within UK government competence. The Assessment has been guided by the Commission's objectives to support sustainable economic growth, improve competitiveness and quality of life, support climate resilience and transition to Net-zero by 2050. Within the Assessment, the Commission identifies some of the key measures and investments required to deliver low carbon and resilient infrastructure for the UK.

Specifically, the Assessment highlights how existing carbon emissions can be reduced through direct changes towards utilising renewable sources for electrical energy generation such as nuclear, offshore wind and solar. The Assessment accepts that this will not be sufficient to cover peak periods where the wind is low and the sun not shining. In this case, renewable sources of energy would need to be supplemented by more flexible generation technologies.

Consequently, the Commission recommended that the government establishes effective business models that incentivise investment in large scale hydrogen and gas fired generation with carbon capture and sequestration and power stations. This could also entail consumers storing electricity on their premises for supplying the grid at peak periods. A move to much more local and mixed generation together with a huge increase in the use of electricity would need the electricity grid to be substantially modified and upgraded.

In addition to decarbonising the generation of electrical energy, the National Infrastructure Assessment also addresses government targets for industrial decarbonisation and transportation. Shareholders and buyers increasingly demand low carbon processes and products. Decarbonising the industrial sector such as steel making requires switching from fossil fuels to a mix of electricity, hydrogen, and fossil fuels abated with carbon capture and storage.

Core networks and infrastructure to produce, transmit and store hydrogen and to transport carbon dioxide for sequestration will be essential by 2035. This carbon capture and storage system should have a capacity of at least 50Mt CO₂ and be based at UK refineries and the core sites where large volumes of CO₂ are generated. A hydrogen pipeline network would connect these sites and others where hydrogen can be produced and used as a fuel instead of oil and gas.

The National Infrastructure Assessment also considers the use of energy at a more local and domestic level. The Commission proposes measures including a number of one-off investments to kick start the market for heat pumps across the public and private sectors. Increasing the adoption of electric vehicles, zero emission buses, mass transport systems and the electrification of remaining main line rail services will be key to decarbonising surface transport. In association with this, the commission also recommends continued transport enhancements and better maintenance of roads to improve traffic flows and reduce congestion

The Commission notes that the UK's infrastructure faces increasing exposure to shocks including those from the environment because of climate change. Engineering systems will need greater resilience to tolerate extreme loads and temperatures than they may have previously been designed for. The public will expect existing safeguards for protection for health and safety and the environment to be maintained. Therefore, the design, manufacture and operation of infrastructure optimised for a low carbon future will need to have engineering structural integrity at least matching current performance over a longer life.

Appendix 2

ESI Challenges for New Nuclear Reactors

Nuclear generation will continue to contribute to a low carbon electricity system. By 2035 8GW of new generating capacity should be available if Hinkley Point C (HPC) and Sizewell C (SXC) come on-line as planned. The UK government is developing the options to deploy advanced modular reactors in a bid to drive down manufacturing costs. It is currently inviting designers to submit proposals for small modular reactors (SMRs) for assessment and is exploring the possibilities for high temperature gas reactors (HTGRs). In addition, EDF Energy is planning to extend the life of the Sizewell B reactor to 60 years.

Papers by James et al [12,13] have presented an analysis of the possible difficulties in gaining regulatory acceptance of the generic design assessment of modular reactors and have highlighted some of the technical challenges to be overcome. The papers focus on potential developments in manufacturing that could drive down costs. These exploit the modular design where the modules of the plant can be produced in volume with economies of scale using factory-based digital manufacturing techniques and requiring less on-site work.

Small modular reactors

By their nature, Small Modular (Pressurised Water) Reactors (SMRs) will be compact in design and occupy a smaller space than their larger counterparts. The modules would be transported to site as large units for final assembly and the impact of transportation on their engineering structural integrity would need to be assessed. Lower fluid volume would require high rates of heat transfer, faster pumps and fluid flows, and a responsive and rapid control system. Potentially frequent and rapid changes in fluid temperature could create the conditions for thermal shock and temperature differences which would exacerbate thermal fatigue while the high-power density could give rise to irradiation embrittlement.

The James paper identified the following areas that are likely to create challenges for designers and regulatory acceptance through generic design assessment (GDA). The UK regulatory environment is robust and demanding so the challenges for gaining acceptance are likely to be considerable. Evidence for engineering structural integrity will need to be generated if regulatory acceptance of a completely new design and manufacturing concept is to be achieved.

- Component classification and interpretation of international design codes
- UK regulatory requirements in GDA additional to code compliance
- Electron beam welding and other advanced joining technologies
- Hot iso-static pressing (HIP) and additive manufacturing technologies
- Modular build process and acceptance of the module after transportation

- Inspection of small/compact components and assemblies
- Local variations in operating modes and load-following
- Ageing mechanisms including irradiation embrittlement and thermal fatigue
- Definition and analysis of transient and accident states
- Secondary consequences in event of a leak or break

Advanced modular and high temperature gas reactors

For Advanced Modular Reactors and high temperature gas reactors that are designed to operate at ultra-high temperatures, the properties and performance of existing metallic materials is not established, and the application of non-metallic materials is at an early stage of development. The James paper identifies the following technical challenges to engineering structural integrity that would

need to be overcome. These challenges are probably on a longer timescale than those for SMRs but still need work now if these reactors are to be an option in the near future.

- Adequacy and sufficiency of existing international codes and standards
 - UK regulatory requirements in GDA additional to code compliance
 - Properties and in-service performance of new materials
 - The stability of moderator materials such as graphite and alternatives
 - Effect of the gaseous coolant (CO₂ or He) – carbonisation, embrittlement
-
- Thermal fatigue from differential thermal stripping
 - Creep properties at ultra-high temperatures beyond existing ranges
 - Environmental fatigue of non-aqueous coolants
 - More simplified and streamlined life-time assessment procedures

The Nuclear Innovation and Research Advisory Board has provided advice to the government on the research and development requirements to deliver its civil nuclear power objectives which has contributed to a five-year Nuclear Innovation Programme. This needs to be integrated and aligned with a UK strategy for ESI.

Appendix 3

ESI Challenges for Hydrogen Storage and Pipelines

Decarbonising the industrial sector in the UK will require switching from fossil fuels to a mixture of renewable electricity, hydrogen, and fossil fuels abated with carbon capture and storage. The National Infrastructure Commission has recommended construction of a core hydrogen gas network to connect the most likely initial sites of hydrogen demand, production and storage, including Grangemouth and Northeast Scotland, Teesside, Humberside and South Wales. Hydrogen storage will be essential to ensure access to sufficient fuel when there are shortfalls in renewable electricity supply. The commission has, however, ruled out supporting direct hydrogen heating of premises to enable exclusive focus on switching to forms of electric heating.

Current proposals are to store large volumes of hydrogen in salt caverns. The core hydrogen network will comprise welded pipelines from converting existing natural gas pipelines to hydrogen service. These pipelines are generally a mix of strength grades of carbon steel depending on the pressure. The main threat to their integrity from hydrogen service is the increased risk of hydrogen embrittlement and cracking which could initiate a long fast running crack.

Hydrogen embrittlement and cracking

Hydrogen embrittlement and cracking have long been recognised in systems where corrosion results in the absorption of atomic hydrogen produced at the surface into the metal. It has typically been associated with structures that have highly negative cathodic protection, such as found in offshore structures. The performance of steels exposed to pure gaseous hydrogen or hydrogen blended with other gases is a more recent topic for investigation.

The kinetics of hydrogen embrittlement and cracking are complex, and many questions remain. The scale and rate of embrittlement depend strongly on the microstructure of the parent and weld material which controls the diffusivity and solubility of hydrogen within the metal. They also depend on the composition and pressure of the gas, including blending gases, and the thickness and temperature of the material. The mechanisms for hydrogen embrittlement are material specific and are not well understood. There are several competing theories.

University research

Several UK universities have research groups working on the fundamental mechanisms of hydrogen embrittlement. These include Oxford, Cambridge, Bristol, Manchester, Imperial College and Queen Mary College London. The view of academics is that the UK is still strong in the field but losing capacity to US and the EU institutions.

There is no current Centre for Doctoral Training for PhD work on hydrogen embrittlement and funding is reliant on intermittent projects from industry. An example is the work that Shell is supporting at Oxford University utilising recent advances in computing power. A coupled multi-physics model has been developed to predict the material properties of steel exposed to an external hydrogen environment taking account of the different interacting mechanisms.

The research community considers that current funding levels for projects are adequate for the currently available resources of people and equipment. The rate of progress is limited only by the number of skilled personnel and equipment. Universities are finding it hard to retain students after their PhDs as many overseas students return to their home countries or other advanced economies.

Industry research

To avoid the risk of hydrogen embrittlement and cracking in steels, industry research is focused on the determining of a critical maximum level of hardness below which the risk would be very low. Current recommendations for the critical hardness such as in ASME standard B31.12 or AIGA guidance of 235 and 250 Hv may be overly restrictive for the use of existing pipelines. The critical level of hardness may be material grade and strength dependent, and research is required to achieve better resolution, particularly for higher strength materials.

Testing for hydrogen embrittlement in air is difficult because hydrogen leaks out of small specimens as soon as the source is removed. It is generally necessary to test specimens in a hydrogen atmosphere which entails pressurised test rigs used over potentially long periods (e.g. 40 days). The static load test has been replaced by the slow strain rate test and fracture toughness tests, but further development of testing methods would be beneficial.

A substantial amount of research on the repurposing of natural gas pipelines is in progress but needs to be accelerated and widened for a UK hydrogen pipeline network to be created by 2035. The work includes a comprehensive report from the consultancy Rosen on the challenges and mitigations for hydrogen pipelines. DNV has undertaken field trials on natural gas pipelines containing hydrogen at the Spade Adam facility to demonstrate the effect of a pipe failure.

TWI has been active in testing pipeline steels for several years and has built up a significant facility for hydrogen testing. It has made a substantial investment in its equipment for hydrogen testing at pressures up to 450 bar. Recently, it has been partnering the Scottish Gas Network and is planning testing work for Cadent to investigate the fatigue performance of hydrogen charged specimens.

Other work includes projects funded by National Gas Transmission and promoted through the Energy Networks Association (ENA) to assess legacy gas steels to hydrogen embrittlement effects. The ENA has recently launched a project to investigate the effect of surface condition and scale which may shield the metal from hydrogen absorption. Work on the effect of hydrogen on gas pipelines undertaken in other European countries has been co-ordinated through the European Pipeline Research Group to which the UK would benefit from having better connections.

Appendix 4

ESI Challenges for Offshore Wind Turbines

To reach Net-zero by 2035, the UK will need a reliable electricity system running mostly from renewable sources of energy. The expansion of new onshore and offshore wind turbines (OWTs) and the maintenance and life extension of existing structures will play a major role in the energy mix. The National Infrastructure Commission predicts that by 2035, 60GW of offshore wind and 25GW of onshore wind generation should be deployed. A change in the Government's auction parameters has resulted in a surge of applications for new sites.

Offshore wind turbines present many engineering structural integrity challenges throughout their lives. The size of wind turbines has steadily increased over the past twenty years as designers have sought greater efficiency and generating power and is predicted to increase further in the future. Towers are higher and blades longer and the size of these components has scaled up accordingly to accommodate the higher loads. Gear boxes and generating equipment at the top of the tower have become heavier and more difficult to maintain or replace.

Fixed monopile offshore wind structures

Most OWT structures off the UK coast are mounted on a fixed monopile driven into the seabed. The pile and foundations at the base of the structure must be able to resist the moment from lateral wind loads on the blades and ensure the tower is stable and remains vertical within tolerance. The continued stability of foundations and connections between the pile and the transition piece as OWTs age and enter the life extension phase are uncertain and further research is needed to be able to monitor and predict their future performance.

Varying wind and wave loads produce cyclic stresses and fatigue damage in the structure at the welded connections of the monopile, transition piece and tower. The circumferential welds of monopiles are vulnerable to fatigue cracking near the mudline where the cyclic loads are highest and around splash-zone where corrosion increases the rate of fatigue damage. Some monopiles are heavily corroded resulting in a loss of wall thickness and pitting which can act as an initiator for a fatigue crack. Fabrication quality of the welding of towers has not always achieved the specification and undetected manufacturing and welding defects could become a source of cracking in the life extension phase.

The sections of the structure are joined by flanged and grouted connections which cannot be replaced. Techniques to monitor their stability and assess the integrity will be needed to take decisions about extended life without risking collapse.

Large bolted flanged connections connecting the monopile and the transition piece and the transition piece and the tower have their own integrity challenges. Loss of bolt pretension requires very costly bolt retightening to maintain the compression between the flange faces under the bolts, and this can also be undermined by lack of flatness and localised corrosion of the mating flange faces. Loss of flange compression renders the bolts vulnerable to a large increase in the rate of fatigue damage and ultimately bolt failure.

Increases in the height of OWTs has meant that the size of bolted flange connections is becoming unrealistically large with bolts of up to 100mm diameter. A significant effort has been made to produce a different design of connection that will transfer the moment load down the structure while avoiding the pre-tensioning and fatigue problems of bolted flanges. The C1 connector is a promising design but further research is needed to minimise the cyclic stresses.

Blades

As blades get longer, the tip speed increases and increases erosion and other blade damage. With the increasing length of blades, leading edge corrosion is an on-going problem. Improved techniques are needed for monitoring and inspection. While drone inspection and autonomous techniques are being developed, improvements to the generation, quality and processing of the images will be necessary to locate and characterise the damage for engineering assessment where there will undoubtedly be opportunities for applying artificial intelligence and machine learning.

Improved blade coating technologies will be needed for better resistance to corrosion and rain damage. Recycling/refurbishment of worn blades is still a major problem. Solutions to repair damaged blades in-situ are needed to avoid the high costs of detaching them and bringing them to shore.

Floating offshore wind turbines (FOWTs)

With shallow water sites in the North Sea running out, floating OWTs are being considered where water depths are too deep for fixed monopile designs. Cost is a major obstacle for FOWTs. They will require bigger turbines to be economic given the higher costs of the supporting structure and distance from the shore.

Several concepts of FOWTs are being developed of which the spar is the most popular. FOWT structures require sophisticated mooring and anchor systems and ballast and weight distribution to maintain the stability that is essential for keeping the tower upright. Optimisation will require complex analysis of fluid structure interactions and mooring chain tension and fatigue.

The UK is leading the way in FOWTs with the Scot-wind project planned to generate 30GW. There are significant opportunities to use technology developed for floating structures in North Sea offshore oil and gas sector that will need to be exploited. Collaboration with international partners needs to be encouraged to advance the technology at the highest possible rate.

Life extension

As OWTs age their demands for maintenance substantially increase. There are a limited number of supply vessels available to ferry installation and maintenance crews to site with the result that maintenance tasks are often delayed or deferred. This is only one of several supply chain issues that are compromising the integrity of offshore wind turbines and their potential for life extension.

Sources of research and expertise in the UK

Over the past ten years the Carbon Trust and the EPSRC has funded an extensive programme of research on topics relating to ESI at UK universities including Strathclyde, Cranfield, Edinburgh and Oxford. A Centre for Doctoral Training (CDT) on renewable energy marine structures (REMS) has had two cycles of funding research on many of the topics mentioned above. An application for a further cycle of REMS funding has not progressed resulting in a decline in research on offshore structures in favour of power electronics and environmental issues.

Engineering companies in the UK offshore wind sector are reporting a shortage of fully qualified structural engineers to lead OWT projects. They have commented that there is no systemic training route such as the CDT that will introduce new graduates to the structural problems of the offshore wind sector. Offshore wind companies are recruiting large numbers of engineers to work in the sector but are having to provide the necessary training themselves.

A key strength of the UK offshore wind sector is the extensive experience derived from historical North Sea oil and gas infrastructure projects as well as more recent OWT infrastructure development. Its ability to export this knowledge and experience and provide engineering services for new OWT projects to a worldwide market is generating significant revenue for UK consultancy and R&D firms. There are, however, significant threats to the UK's leading position in engineering consultancy and services that could if not addressed result in the UK losing its competitive edge within the next decade, if not sooner.

There is increasing global competition in the offshore wind sector, particularly with the ambitious growth targets set in China and the US. While the US renewable energy market may be influenced by political shifts, China's steady growth poses a challenge that the UK companies must be ready to meet. Additionally, with substantial financial incentives for Net-zero focused fundamental and applied research in European countries like the Netherlands, Germany, and Denmark, there is already a noticeable shift in offshore wind R&D leadership from the UK to mainland Europe. As a result, the UK's thought leaders and specialised workforces may be drawn to the European and other overseas businesses where greater opportunities and incentives are readily available.

It is therefore important that UK research funding is sufficiently broad to address the challenges of new designs and global markets as well as the fundamental and applied needs for integrity management of aged OWT structures in UK waters. The UK will need to invest to maintain its expertise and leadership in offshore wind technology. If it does so, then the rewards from growth of UK based companies in the global offshore wind market could be very significant.

Appendix 5

ESI Challenges for Carbon Capture and Sequestration (CCS)

The UK's future demand for energy will require the burning of fossil fuel mostly in the form of natural gas. Reducing carbon emissions will require capturing the CO₂ from the flue gas emitted from power stations and industrial sites, compressing it to a denser form at high pressure, and transporting the dense gas by pipeline to underground storage in exhausted oil and gas reservoirs. There are significant ESI challenges at every stage of the process.

The UK has created clusters of gas fired plant where the emissions will be connected and pumped through existing pipelines to reservoirs in the North Sea and Liverpool Bay. They include the Scottish Cluster, the East Coast Cluster, Hy Net (Northwest England) the Solent Cluster and Bacton Thames Net Zero. New gas fired power stations planned, such as the one at Peterhead, will be built with CCS technology capturing 1.5Mt of CO₂ annually.

The carbon capture process starts by cooling the exhaust flue gas. The cooled flue gas is passed through an absorber containing an amine which preferentially absorbs and separates the CO₂ from the other combustion products which are released to atmosphere after filtering. The CO₂ rich amine is passed into a regenerator where it is heated releasing CO₂ leaving the lean CO₂ amine to be recirculated. The CO₂ released from the regenerator contains water and requires drying and compressing to a dense form for pumping into reservoirs.

A full-scale pilot project at the Boundary Dam Power Station in Canada has illustrated the ESI problems that CCS plants will experience. The project is the world's first post combustion CCS plant fully integrated with a coal fired power station and commenced carbon capture in 2014. Although the flue gas composition is slightly different from a combined-cycle gas turbine (CCGT), the principles of the technology by absorption using an amine are the same.

The plant was spread out over the site and an early issue was the potential for leakage at the expansion joints between the sections of the plant. For the cooling of the flue gas, a key design consideration of indirect colling where flue gas of varying temperature flows over tubes filled with a cooling medium is acid dropout locally attacking the tubes resulting in significant corrosion. Before the cooled flue gas enters the absorber, its pressure is boosted by a large fan where deposits from the gas caused excessive vibration. Particulate build-up was also a problem for the amine absorber unit and was associated with amine degradation. Controlling the supply of steam and temperature of steam into the regenerative boiler was difficult and was a potential cause of fatigue cracking.

There is substantial experience from the oil and gas sector of transporting CO₂ through carbon steel pipelines. There are normally few operational issues providing water and oxygen are managed, but for CCS mixed source CO₂ streams from several industrial sources pose a challenge in terms of impurities present. Oxides of nitrogen and sulphur present a risk of pipeline corrosion while a mixture of CO-CO₂ has the risk of stress corrosion cracking. These risks depend on the composition and microstructure of the parent steel and welds and the partial pressure of the gases involved.

The performance of materials exposed to dense CO₂ is not well understood. Research requiring substantial testing is needed to characterise the performance of existing steel pipelines to dense CO₂ at different partial pressures with water vapour and oxygen present. As pilot CCS plants are being constructed, research work to validate the use of the existing pipelines is urgently required.

Appendix 6

Members of the Advisory Committee

Professor Mike Fitzpatrick FREng (Chair) – Coventry University

Professor David Knowles FREng (Royce) – University of Manchester

Professor Andrew Sherry FREng – University of Manchester

Professor Peter Flewitt FREng (FESI) – University of Bristol

John Sharples (FESI) – Jacobs

Peter James - Jacobs

Paul Smith – Jacobs

Professor David Nash – University of Strathclyde

Professor Ali Mehmanparast – University of Strathclyde

Professor Ferri Aliabadi – Imperial College

Professor Bo Chen – University of Leicester

Professor Peter Loftus (RCNDE) – University of Bristol

Eleanor Crossley – Office for Nuclear Regulation

Mike Martin – Rolls-Royce

Professor John Wintle – TWI Ltd/University of Strathclyde

Dr Paul Woollin – TWI Ltd

Project Team

Professor Mike Fitzpatrick FREng (Chair) – Coventry University

Professor David Knowles FREng (Royce) – University of Manchester

Professor Peter Flewitt FREng (FESI) – University of Bristol

John Sharples (FESI) – Jacobs

Professor John Wintle – TWI Ltd/University of Strathclyde

Appendix 7

Experts Consulted Individually

Person	Organisation	Topic
Mahmoud Mostafavi	University of Bristol	Fracture/failure assessment
Janice Barton	University of Bristol	Composites
Bruce Drinkwater	University of Bristol	NDT/monitoring
Paul Wilcox	University of Bristol	NDT/monitoring
Chris Trueman	University of Bristol	Solid modelling
Simon Lewis	EdF (ex FNC)	AMR/structural modelling
Peter Loftus	Independent	NDT/monitoring
Cory Hamlin	UKAEA (Culham)	Fusion/materials modelling
Emilio Paneda	University of Oxford	Mechanistic modelling
Ferri Aliabadi	Imperial College	Aerospace/transportation
Mike Martin	Rolls Royce	SMR/probabilistic methods
Bo Chen	University of Leicester	AMR/ high temperature effects
Paul Smith	Jacobs	PWR (SXB, HPC, SZC)
John Stairmand	Jacobs	PWR (SCC and fatigue)
Bernard McGrath	Jacobs	Advanced NDT
John Sharples	Jacobs	Fracture and fatigue
David Knowles FREng	University of Manchester	Research and Innovation
Andrew Sherry FREng	University of Manchester	Data centric engineering/skills
Ali Mehmanparast	University of Strathclyde	Offshore wind
David Nash	University of Strathclyde	Medical devices
Paul Woollin	TWI Ltd	NSIRC/welding/manufacturing
Mike Dodge	TWI Ltd	Hydrogen damage