Nuclear energy materials

Materials UK Energy Review 2007

Report 3 - Nuclear Energy Materials

Contents

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1.0

Executive summary

Improved materials are crucial to innovation in the energy sector, including fission and fusion. Major advances are being made in materials science - in both understanding and techniques.

Focussed, integrated and well-coordinated materials research will make a major contribution to promoting UK strategic objectives for supporting existing fission power plants and developing and supporting new power plants - in the short term fission and, later, fusion.

Such a materials research programme, together with the expertise and infrastructure that it will generate, will benefit and involve a wide range of government agencies concerned with energy and environmental issues, as well as major industrial and supply-chain companies.

Key factors driving the need for research

The key socio-economic drivers are environmental (especially reducing CO_2 impact); economic (obtaining maximum value for money from both existing and new plant); improving security and diversity of electricity supply; ensuring social acceptability; exploiting fission-fusion synergies; and exploiting synergies with the nuclear marine propulsion programme. Technically, most of the items in the resulting Research Agenda can be expressed in terms of the value of extending, and reliably predicting, the ***lifetimes*** of materials and components ***in demanding and potentially damaging environments***.

Accordingly, for fission, research is needed in the areas of fuels, fuel cladding, pressure vessels, core components and cooling systems; containment systems; components in reprocessing plant and waste repository materials. For fusion, although most of the systems are different, many of the materials issues, and most of the research methods, are very similar.

UK focus for the agenda

The focus of the Strategic Research Agenda should be confined to areas specifically addressing UK needs and opportunities, using UK strengths, but effectively linked to European and global research and information networks and experimental facilities *(Recommendation 1)*. Analysis shows that the key UK problems for study include corrosion and erosion; environmentally assisted cracking; radiolytically-induced mechanisms of embrittlement, crack initiation and crack propagation; creep-fatigue interactions; irradiation creep and swelling; thermal cycling; joining and interface technologies; effects of helium; very long term degradation of storage materials; and non-destructive examination methods.

The key infrastructure and facilities required in order to carry out such work are access to irradiation facilities and/or proxy irradiation sources; “hot” working laboratories; autoclaves for environmental testing at plant operating temperatures; creep-fatigue testing equipment; advanced materials characterisation instrumentation; large-scale computer modelling facilities; a comprehensive set of archived material from decommissioned fission reactors for study; and resources for a “knowledge capture exercise” to capture the wealth of experimental data and personal knowledge which is rapidly disappearing from this U.K. industrial sector.

Priorities for UK applied research

Four immediate promising opportunities have been identified that play to UK strengths and would yield substantial progress on key cross-cutting issues. These opportunities arise because of the existence of synergies in experimental and modelling techniques. Accordingly, it is recommended that new or enhanced multi-disciplinary research

programmes, integrated across the whole of the supply chain, should be launched into: mechanisms of in-service and in-repository corrosion and degradation of materials; predicting the behaviour of welded structures subjected to high temperatures and complex loadings; predicting irradiation damage effects in fission and fusion materials; and the development of new and improved methods for non-destructive monitoring and evaluation of materials in service.

(Recommendation 2). This applied research needs to be integrated with the enabling research summarised below.

Underpinning research needs

Substantial new opportunities exist for productive research in the above priority areas, enabled by utilising and developing the recent and continuing major advances in experimental methods for materials characterisation and understanding-based multi-scale modelling of materials behaviour. Materials which need to be studied include austenitic, ferritic and oxide-dispersion strengthened steels; zirconium; graphite; fission fuel materials; refractory metals such as tungsten; and repository materials.

Effective implementation

The key barriers to research progress are lack of financial and human resources; the greatly reduced physical infrastructure and facilities within the UK for nuclear research; and lack of stability of the regulatory and financial regimes. Stability in funding is essential, as is ‘ownership’ of the Strategic Research Agenda by a consortium of key institutions, accompanied by clear leadership and direction, and drawing in the expertise and resources of industry, research institutes, universities, regional development agencies, and the proposed National Nuclear Laboratory *(Recommendation 3)*.

Initially, the strategic research programme should be developed by exploiting existing Core Competencies in the UK and harnessing them in multi-disciplinary Flexible Teams that can be focussed on the critical problems and issues *(Recommendation 4)*. The research should be reciprocally linked to skill base refreshment to develop and retain expertise and knowledge: research that uses the UK inventory of pertinent skills and data is one of the most effective ways - perhaps the most effective way - to maintain/refresh such UK assets *(Recommendation 5)*. A national knowledge management capability is required to ensure that maximum benefit is obtained, both from existing knowledge and from that generated during future research *(Recommendation 6)*.

The fission and fusion materials R&D needs to be linked to other areas of materials R&D where there are significant synergies to be exploited - especially materials for advanced fossil-fuel power plants *(Recommendation 7)*.

2.0

Introduction

Nuclear power is of crucial importance to the future global environment, because it permits large-scale, reliable electricity generation with negligibly small CO_2 emissions.

There are currently about 440 commercial power-generating nuclear reactors operating in 30 different countries. Between them, these plants have a total capacity of 372,000 MWe, and supply 16% of the world's electricity requirements. The USA has the largest number of operational reactors (104). France is in second place, with 59 reactors, and relies on nuclear power for a larger share of its electricity supply than any other country (78%).

An additional 30 reactors are currently under construction in various parts of the world, and more than 80 further reactors are at various stages of planning and development, notably in China, Japan, Korea, India and Russia. In addition to power-generating units, there are about 280 research reactors in 56 different countries. A further 220 reactors are used in marine propulsion systems.

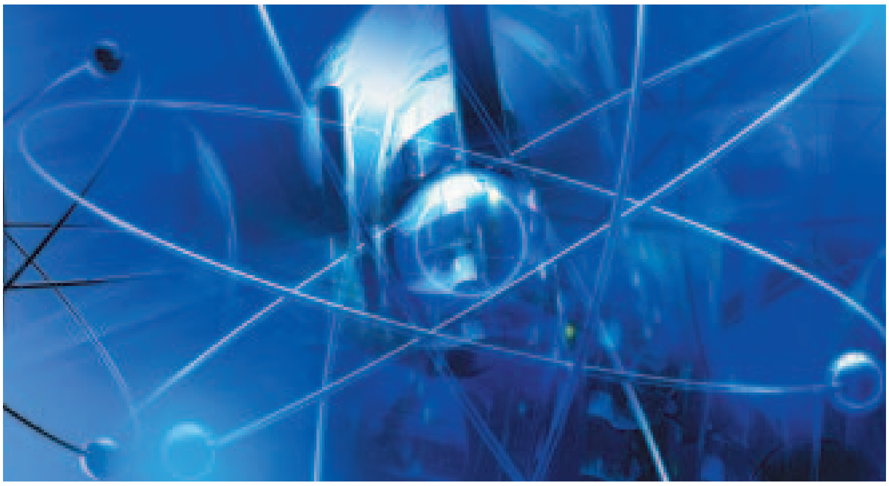
Construction of new power-generating nuclear reactors in North America and Western Europe came to an almost complete halt after the accidents at Three Mile Island (1979) and Chernobyl (1986). However, since that time there have been substantial advances in reactor technology, and in particular the design of safety systems. The so-called "Generation III" advanced light water reactor designs, which are currently available, incorporate passive safety systems that are triggered automatically in the case of an emergency, and do not require auxiliary power sources for their operation. "Generation III+" and "Generation IV" designs are also under development, which promise cleaner and more economical nuclear power towards the middle of the present century. One of the added advantages of nuclear reactors is that they can be used to produce hydrogen via electrolysis or thermal reactions, and can thus play a part in a future hydrogen economy, as well as in the direct production of electrical power.

There is also a major international effort to develop nuclear fusion as a new source of power. If successful, this would remove many of the long-lived nuclear waste problems associated with fission reactors. An international reactor-scale fusion device (ITER), is beginning construction at Cadarache, in the South of France. However, even with optimistic assumptions, it is likely to be several decades before fusion power plants become available commercially.

In the U.K., there are currently 19 operational power-generating nuclear reactors, which produce 18% of the nation's electricity. Most of these reactors are old, and approaching the end of their useful working lives. No nuclear reactors have been commissioned in the U.K. since 1995 (Sizewell B), and none are currently under construction. As a result, the contribution of nuclear power to U.K. electricity supply is predicted to drop to 7% by 2020, and to zero by 2035, unless new construction is undertaken.

Improved materials are crucial to innovation in the energy sector, including fission and fusion. Major advances are being made in Materials Science - in both understanding and techniques. Accordingly, focussed, integrated and well-coordinated materials research, planned to take maximum advantage of the existing knowledge base together with newly emerging experimental and theoretical methods, would make major contributions to promoting UK strategic objectives [1, 2, 3] for:

- Supporting existing fission power plants - especially the economic operation of these, and the safe extension of their lifetimes;
- Decommissioning these plants (and plants now closed) and managing the waste materials arising;
- Developing and supporting new power plants (in the short term fission and, later, fusion) and advanced fuel cycles - aiming at improved economics, safety and security, environmental impacts or operational characteristics;
- Ensuring public confidence in the above;
- Exploiting synergies with research for marine propulsion plant.



2.0 Introduction

> *“The focus is on the UK-specific opportunities, needs, challenges and strengths...”*

The delivery of these strategic objectibes and the expertise and infrastructure that it would generate would benefit (and involve) a wide range of agencies serving the public interest, notably: the government departments, agencies and research organisations concerned with energy, environmental and defence issues; organisations responsible for safety, Health & Safety Executive and the Nuclear Industry Inspectorate (HSE/NII), waste immobilisation, storage and cleanup (Nuclear Decomissioning Authority (NDA) and the Environment Agency). In addition, such a programme would benefit and involve major industrial companies (such as British Energy, Rolls Royce and BNFL), supply-chain companies (such as Serco Assurance and Nexia Solutions), and leading materials-related university departments and research organisations such as TWI.

The discussion in this report illustrates how such materials research can effectively be undertaken. The focus is on the UK-specific opportunities, needs, challenges and strengths, together with the importance of making effective use of links to European and global research, information networks and experimental facilities.

Certain broad themes predominate in this discussion, namely:-

- The need to predict with confidence the behaviour and properties of materials in demanding environments.
- The value of accelerating the design and characterisation of improved materials.
- The great opportunities afforded by new scientific developments to more effectively achieve the above objectives.
- The need to refresh, develop and sustain key UK expertise and facilities in all elements of the supply chain (academia, government R&D, industrial R&D, plant operators and regulators) in a cost-effective way.

These themes are also characteristic of many of the materials research issues for fossil fuel plant which have been highlighted separately in Fossil-fuelled Energy Materials Report.

The crucial factors driving the need for materials research in this sector can be classified into two groups, the broad socio-economic drivers, and those arising from technology requirements. Each of these will be discussed in turn.

3.0 Key socio-economic drivers

The crucial factors driving the need for materials research and development in this sector can be broadly classified as follows...

Environmental

The imperative need is to mitigate climate change without inhibiting world economic development. Recent publications, such as the Stern Review [4] (by the former Vice-President and Chief Economist of the World Bank) and the Intergovernmental Panel on Climate Change [5] have removed most of the residual uncertainties about the cost, reality, causation and pace of climate change. Typical energy/environment/economic scenarios [4, 5] have projected continued economic development (especially of currently less-developed or developing countries), and associated growing energy consumption, throughout this century, accompanied:

- during roughly the first third of this century, by a levelling-off of carbon emissions; and
- during the subsequent two thirds of the century, by the reduction of carbon emissions to levels approaching - or lower than - current levels.

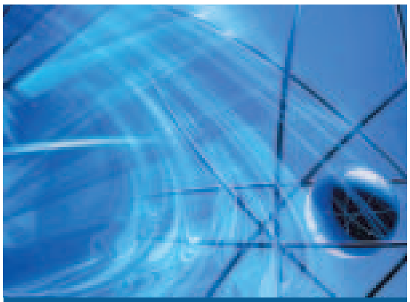
Extending the lifetimes of existing fission power plants; building a new generation of fission power plants, aiming at features likely to maximise social acceptance; and bringing fusion power to practical fruition - will all make major contributions to solving the global environmental and economic [2] problems. As will be shown, materials research is at the heart of the resulting development needs [6, 7]. Furthermore, even for next generation 'turn-key' plants that do not require significant materials development, expertise is required in the UK to ensure appropriate assessment of detailed designs [8] and subsequent regulation of operations.

Economics

Viable economics remains a key requirement. This is a further motivation for lifetime extensions of existing fission plants - as extended plants have by far the lowest avoidable costs of all power generation methods - and for obtaining and maintaining assurance of predicted long lifetimes of newly designed and built plants. More generally, materials performance is key to maintaining confidence in the total engineering system. For fusion power plants economics motivates the development of materials for high temperature operation and prolonged component lifetimes, in order to secure high availability.

The regulatory environment

Integral to the economic and environmental drivers is proper attention to plant safety and regulation. The non-prescriptive regulatory regime in the UK, where the plant operator has to demonstrate the safety of the plant rather than comply with externally prescribed design/operating codes, imposes significant requirements on the level of expertise in all elements of the supply chain [9]. The operator must be both an intelligent customer for, and an intelligent owner of, the entire system. A continuing supply of appropriately trained personnel is therefore essential.



CRUCIAL FACTORS

- Environmental
- Economics
- The regulatory environment
- Security and diversity of supply
- Maximising Social Acceptability

Security and diversity of supply

This provides an obvious justification of new build fission and, in the longer term, fusion, and for lifetime extension of existing plants, but with no materials research implications further to the earlier points.

Maximising Social Acceptability

The successful demonstration of good solutions to decommissioning and waste management issues is essential for maximising public acceptance. It is important to be able to show the reliability of the new materials and systems involved. Research to forward a variety of materials developments, innovative solutions and predictability would be helpful to support this debate [10].

4.0

Technological drivers for research

The research agenda is driven by the need to reliably predict operating plant service life and operate plant optimally.

Key considerations are the degradation of materials properties, and time dependent failure processes for structures and components, including joints and welds. In the case of new and more advanced power plants, it is necessary to optimise new materials to extend those lifetimes, based on understanding of the mechanisms of specific time-dependent phenomena such as irradiation damage, creep, corrosion, and sub-critical crack growth, and the mechanisms of the interactions between them.

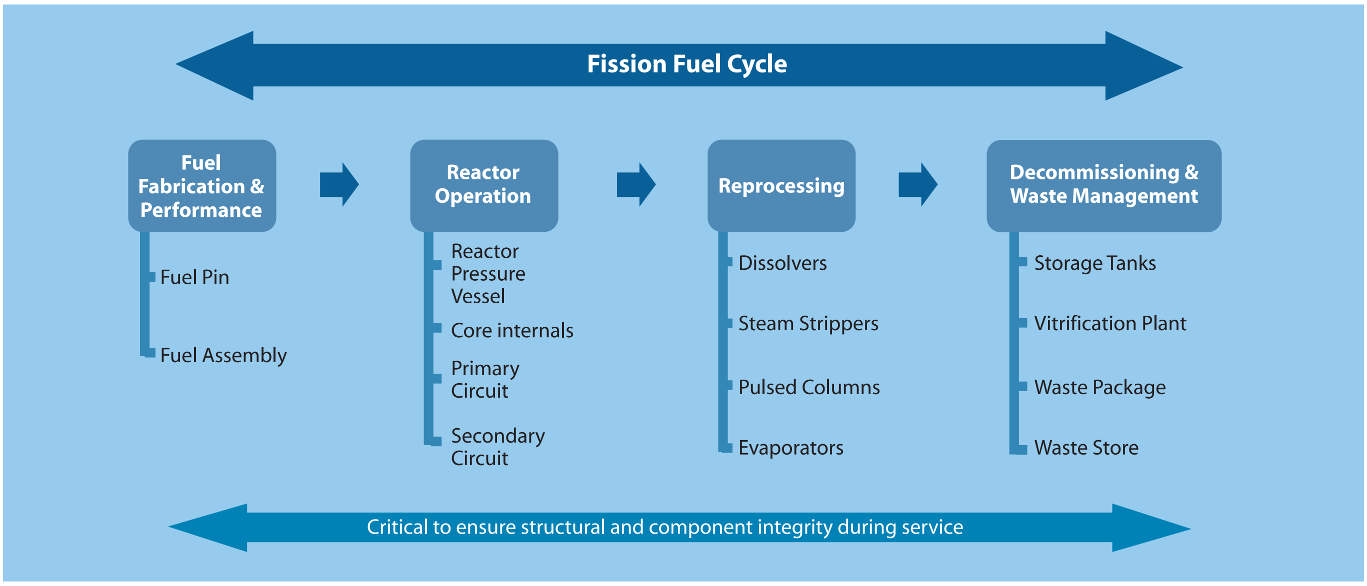
Specific material challenges apply also to facilities associated with reprocessing, and waste immobilisation and management. It is clear that materials research/expertise is required on several timescales.

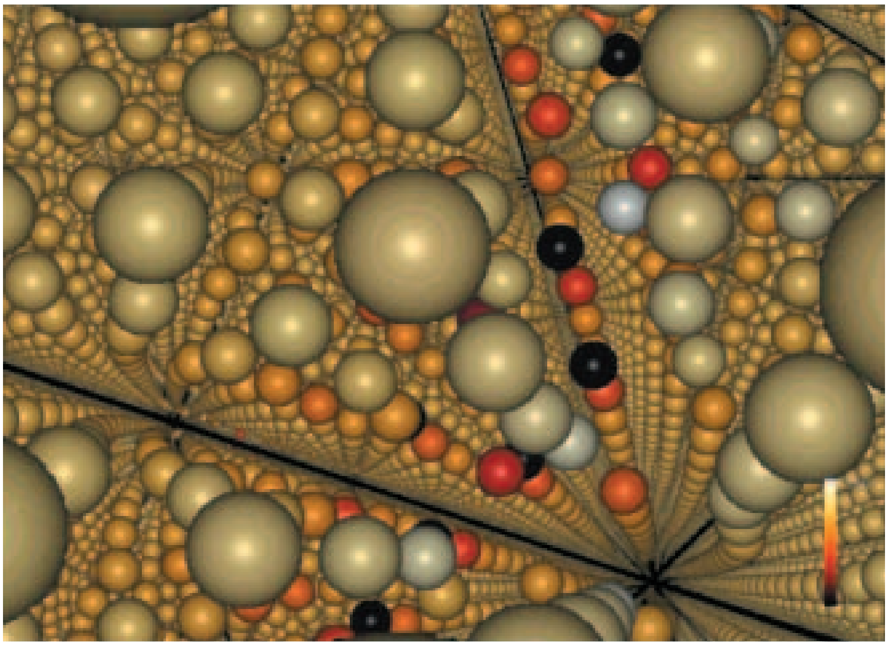
- **During the next 5 years:** to maintain and most effectively exploit the existing fleet of fission power stations (gas-cooled Magnox and AGRs, and a water-cooled PWR); to address issues associated with the operation of re-processing plant and short-term waste storage; to assess and regulate new build power stations; and to develop optimised materials and components for testing in a fusion materials irradiation facility.
- **Over a 5-10 year time span:** increased focus on the new build and fusion issues, which places increasing emphasis on developing materials to withstand high temperatures and high levels of irradiation damage; together with the need to address re-processing and de-commissioning issues and be able to predict the long-term evolution of the behaviour of repository wastes.
- **Over a 10-20 year horizon:** to exploit with optimum efficiency the operation of the fleet of new build fission power plants; to develop emerging/advanced fission reactors; to predict with confidence the behaviour of repository material over periods of many centuries; and to finalise the selection of materials for a fusion demonstration power plant.

The main components which are incorporated in the activities which comprise the fission fuel cycle are shown in Figure 1. This figure illustrates the wide range of components involved. The environment to which materials are subject depends on the component but may involve exposure to high temperatures, neutron irradiation, external (and internal) stresses, and corrosive liquids.

For existing plant the primary driver for materials research is the need to predict reliably the through-life properties of components such as the reactor pressure vessel or certain core components that experience high temperatures and/or are exposed to high fluxes of neutrons. In addition, advanced materials with improved corrosion or oxidation performance are still being developed for components such as fuel cladding. Similarly, the need to minimise the cost of re-processing, decommissioning and waste management is leading to increased materials research into specific materials degradation mechanisms relevant to immobilisation materials, such as glasses and ceramics, and containment vessels in chemical plant supporting re-processing.

Figure 1. Main activities and components of the fission fuel cycle





An illustration of the power and utility of modern materials modelling methods. This shows a computational simulation of about a million atoms of iron in a distorted configuration of the crystal lattice such as can be produced by bombardment by neutrons. Such distortions are ultimately responsible for creep, swelling, etc. The forces between the atoms have been calculated by a new approach that takes into account the magnetism of iron at the atomic level. The colouring of the atoms reflects the strength of their magnetic moments

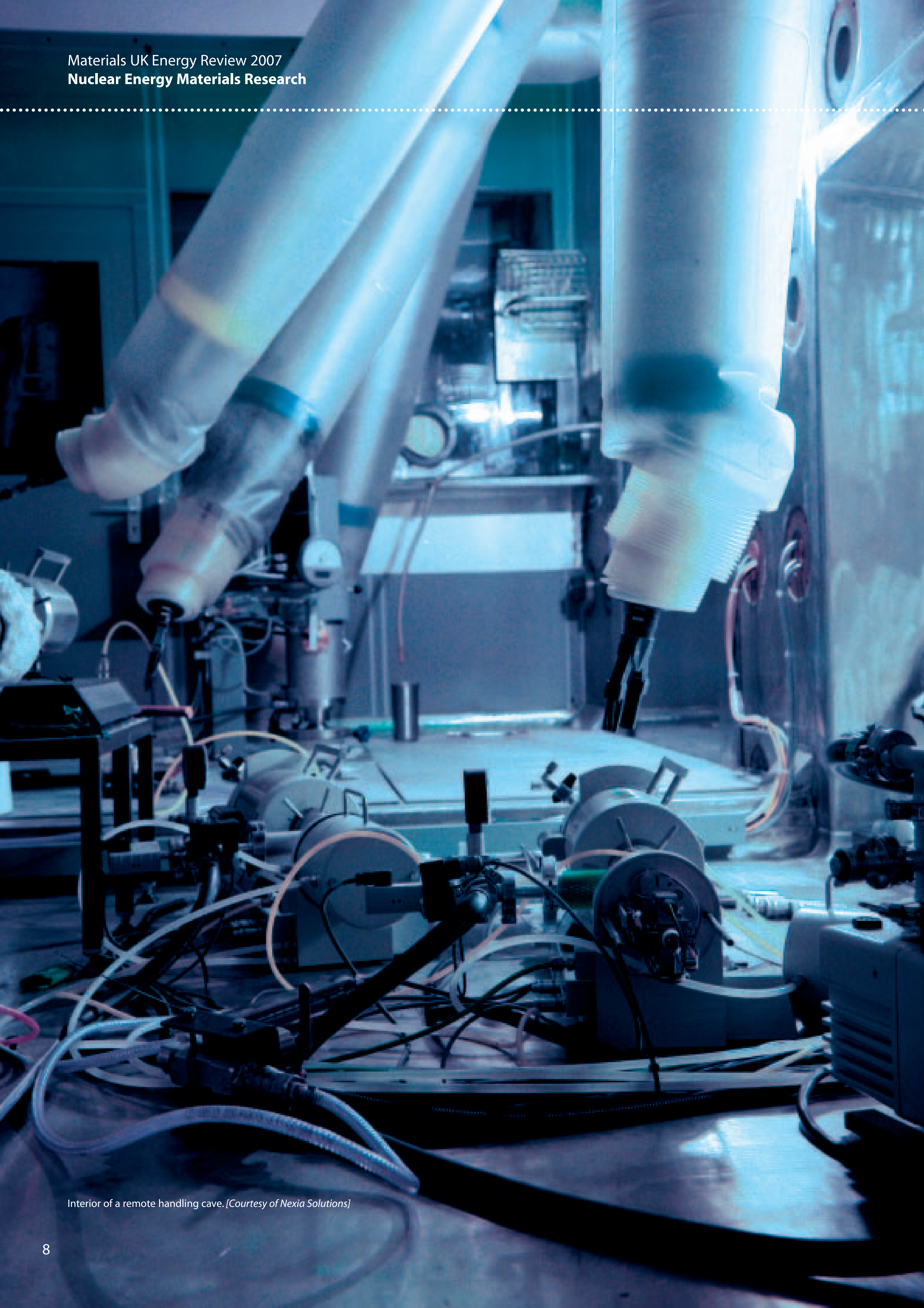
Cut-away view of an intermediate level waste container

For advanced fission reactor systems the main driver is for materials research to develop new materials which are resistant to deleterious dimensional and mechanical property changes caused by exposure to high temperatures and high fluences of neutrons.

Overall, R and D is needed in the areas of: fuels; fuel cladding; pressure vessels; core components including graphite moderators and cooling systems; containment systems; components in reprocessing plant; decommissioning and waste immobilisation and repository materials.

For fusion, most of the systems are different. However, there is a wide range of commonalities in the materials issues. There is an overlap in the classes of materials employed and in the effects responsible for material and component degradation, and the research methods - experiments and modelling - are similar for a broad range of issues. Specific additional problems arise in the case of plasma-facing components, due to damage caused by the impacts of high-energy ions.

> *“For existing plant the primary driver for materials research is the need to predict reliably the through-life properties of components...”*



Interior of a remote handling cave. *[Courtesy of Nexia Solutions]*

5.0

Research opportunities and challenges

5.1 Approach

The research opportunities and challenges are not just related to identifying key research issues associated with current and future plant. It is important also to reverse the decline in the UK capability in this area.

Well-focussed materials research programmes must play their part in helping to promote the development of individuals who can enter all elements of the supply chain to ensure the creation and execution of programmes to address crucial issues, and lead the assessment and regulation of both new designs and plant life extension of existing plant. To be truly effective an enhanced industry/government/academic partnership is needed, which addresses both the short term commercial and the strategic imperatives - it is critical for success that an organisation, or consortium of organisations, ‘owns’ this strategy.

We address these needs by developing a strategic research agenda. This is initially based on analysing existing UK Core Competencies (in research institutes, academia and industry with its associated supply chain) and exploiting these in Flexible Teams that can be focussed on the critical problems and issues. The nature of the research opportunities is such that the flexible teams need to be multidisciplinary in character. In a second phase, a case for further development of these core competencies will be made.

A strategic, and broadly common, research approach to most of the crucial materials problems and underlying phenomena is required. The approach proposed here is predicated upon four major considerations:

1. Bombardment by neutrons, characteristic of fission and fusion power plants, gives rise initially to atomic scale changes in the internal microstructure of a material, primarily through displacing atoms and generating helium and hydrogen atoms by transmutation reactions. The effects then propagate up through the length scales to generate a series of further changes.
   The primary research challenge is that of passing reliably, via understanding and modelling, from observations at the small temporal and spatial scales characteristic of such changes to the large scales characteristic of the in-service environment. It is important to maximise the amount of information which can be inferred from small samples and modelling.

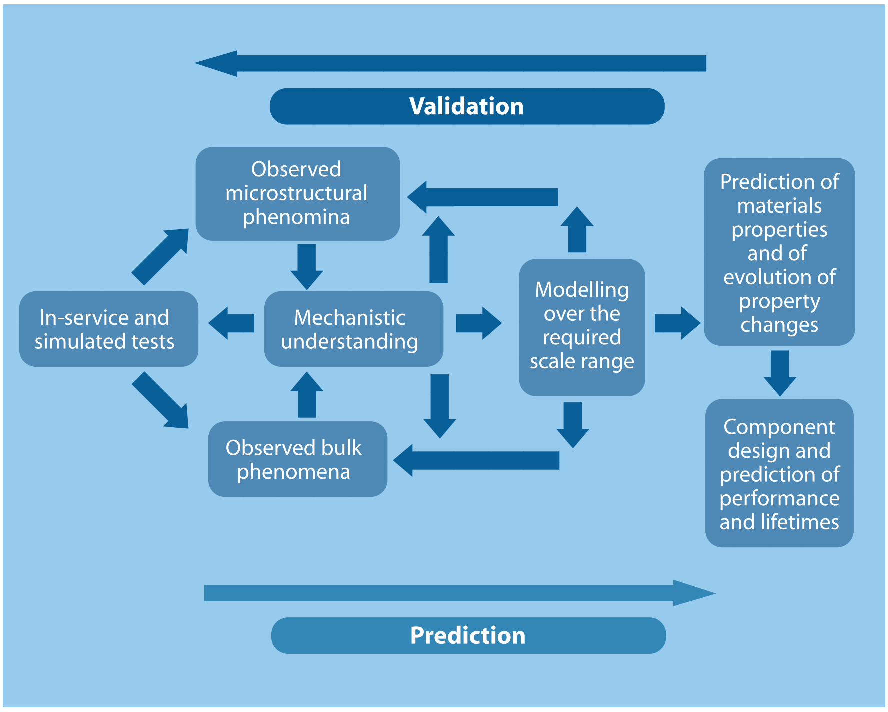


Figure 2. Elements of a strategic, and broadly common, research approach to most of the crucial materials problems and underlying phenomena.

5.0

Research opportunities and challenges

2 It is essential to develop and validate mechanistic understanding, which enables data obtained in an experimental simulation of certain aspects of the in-service environment to be used to predict the performance of materials over the lifetime of a component. Indeed, central to this approach is the value of a mechanistic understanding of the microscopic effects in order to understand change in bulk properties and the need to build predictive models of component performance.

3 Material properties have to be predicted for components in complex situations involving exposure to different combinations of high temperature, stress, fluxes of neutrons and gamma radiation, and gaseous, aqueous or other corrosive environments. The requirements include a fuller understanding of the behaviour of complex welded engineering structures.

4 Repository materials, which include cements, ceramics, glasses and metal alloys, will be stored over very long periods. As a consequence, it is necessary to develop innovative solutions and underwrite safe storage over these timescales. Therefore materials have to be selected, and properties predicted, based upon data obtained from shorter term tests that are representative of the appropriate geological conditions.

These considerations demonstrate the need for a combined modelling-validation-understanding approach to meet the engineering challenges of the industry at large. The elements of such an approach are shown in Figure 2.
It should be noted that there are many common features in methods of experimental and theoretical investigation between fission and fusion materials issues, and substantial overlaps in the types of material and challenging phenomena. In addition, dependent on plant design, there are a wide range of materials ranging from those of general industrial usage such as ferritic and austenitic steels to those more particular to the nuclear industry such as zirconium alloys, graphite, ceramics and oxide fuels.

Although the issue of irradiation damage is exclusive to the fission and fusion sectors, similar considerations to those summarised above apply more widely: to predicting the response of materials to other challenges such as high temperature operation - where there are significant synergies with work needed for advanced fossil-fuel power plants - and to the design of improved materials.

These considerations allow us to broadly classify the core competencies and facilities that are required namely:

High level waste containers. *[Courtesy of Nexia Solutions].*

- Experimental techniques for determining the changes in (bulk) physical, dimensional, mechanical and corrosion properties of materials occurring either during service, or during simulation tests.
- Experimental characterisation techniques to determine the microstructural changes in in-service or simulation tests. These techniques include methods such as tomographic microscopy, in-situ time-resolved (as well as conventional) electron microscopy, scanning probe, three-dimensional atom probe, focussed ion-beams for imaging and milling, high resolution energy loss electron spectroscopy, extended X-ray absorption fine structure measurement, X-ray magnetic dichroism, neutron scattering and spectroscopy, and electron spectroscopy for chemical analysis.
- A toolbox of theoretical modelling techniques that enable simulation of materials behaviour across a wide range of scales. Such techniques include density functional theory, atomistic dynamics, kinetic Monte Carlo methods, and dislocation dynamics, validated by the experimental observations.
- Proxy irradiation facilities, such as ion-beams, focussed particularly on model validation. Unfortunately, only minimal facilities of this kind are now available within the UK. This puts a considerable premium on access to European and global facilities. It should be noted that important ion-beam facilities that are dedicated to materials research are being developed by the University of Manchester at the Dalton Cumbria Facility and at the University of Salford.
- Assured access to irradiation facilities in materials test reactors (MTRs). This is particularly important for carrying out long term tests to validate extrapolations based on short term test data or proxy irradiation and modelling. There are no MTRs in the UK and it is currently difficult to get access elsewhere in the world for the right kind of irradiation, or for sufficient length of time (for example, to enable the interaction of irradiation with corrosion to be studied).

- Facilities that allow the examination of activated or contaminated material. Such a capability may be provided by the proposed National Nuclear Laboratory (NNL), based on facilities at Sellafield. In the context of research to be proposed, it is important that these facilities be made available, through NNL, for research carried out by researchers other than NNL staff.

It is important to note that there are now major opportunities to be exploited from the new advances in materials characterisation methods and in modelling. Achievements that would have been thought impossible a decade ago are becoming routine.

The process for determining the issues to focus on initially is illustrated in Figure 3.

The final step is to identify cost-effective and productive research programmes that will energise existing and potential teams, as illustrated in Figure 4.

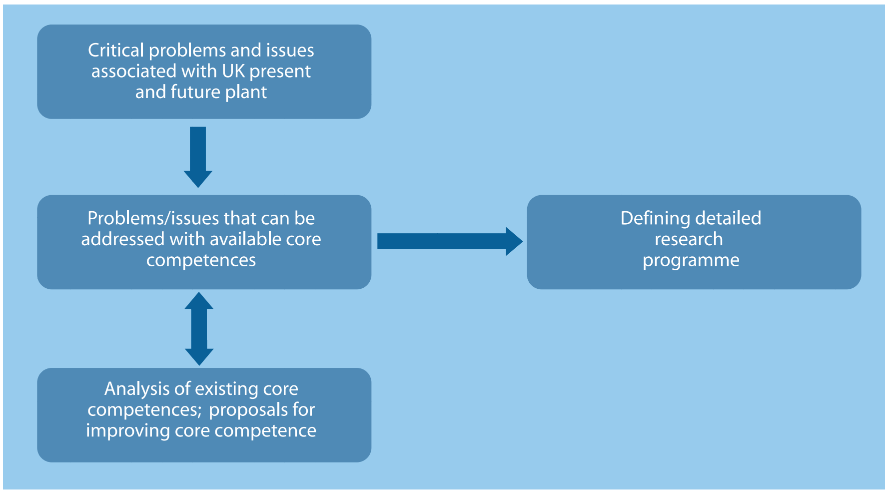


Figure 3. Outline of the process for determination of the initial research programme

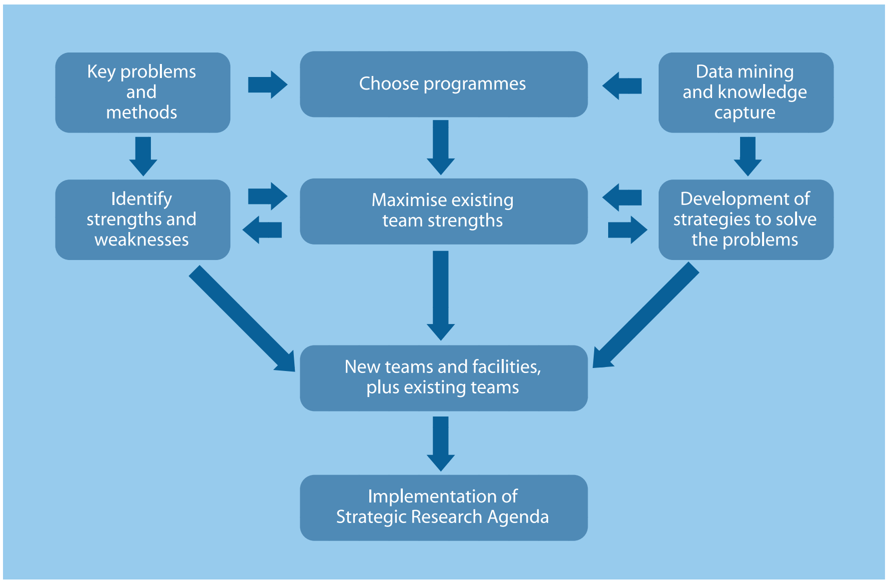


Figure 4. Identification of cost-effective and productive research programmes.

Studies of pertinent materials have been widely undertaken over the past sixty years, and it is important to maximise the benefit of these studies to future programmes of research by appropriate data mining and knowledge capture exercises. Similarly, it is vital to identify long-term exposed materials from surveillance programmes or decommissioned plants/components that should be retained for examination and may be used for future validation of models.

The maintenance in the UK of an adequate base of skills and knowledge is essential for the most effective prosecution of the strategic research. This is not by any means an exclusively UK problem, it is fairly general throughout Europe and the world. In this connection, it should be noted that:

- Research that uses the UK inventory of pertinent skills and data is one of the most effective ways - perhaps the most effective way - to maintain/refresh such UK assets.
- The strategic research needs to be effectively linked to European and global research and information networks and experimental facilities. Currently, only the fusion materials research programme has achieved this level of integration. Similar integration is required for the other areas identified in this report.
- A national knowledge management capability is required to ensure that maximum benefit is obtained, both from existing knowledge and from that generated during future research.

5.0 Research opportunities and challenges

5.2 Detailed research issues

The critical materials problems and issues associated with UK present and future plant are classified into three broad categories, namely behaviour at high temperature, irradiation damage and behaviour (including stability) at ambient - or near ambient - temperatures. The most immediate challenges and opportunities associated with the materials of main interest are identified in the Table opposite. The key methods for solution of materials problems and key gaps in UK capabilities are also summarised.

In addition the safe and economic operation of nuclear power plant structures and components over the complete life cycle is reliant on effective and reliable non-destructive examination and plant monitoring. Over the service life there is a need to monitor any degradation of the structures and components, including materials properties that can undermine continued safe performance. The development of improved non-destructive methods for monitoring the behaviour of materials during service is a further area of key importance. Within the fuel cycle shown in Section 4 these span short (fuel manufacture) to geological time-scales for the storage of waste.

	Behaviour at high temperature	Irradiation damage	Behaviour/stability at near-ambient temperatures
Main materials of interest	Austenitic, ferritic and ODS steels. High-nickel alloys Zirconium Alloys. Tungsten. Graphite	Austenitic, ferritic and ODS steels. Zirconium alloys. Graphite. Fission fuels. Tungsten.	Repository materials, including cements, glasses and polymers. Austenitic, ferritic and ODS steels. High-nickel alloys Zirconium alloys. Graphite.
Main problems	Creep-fatigue interactions. Thermal cycling. Joining and interface technology.	Irradiation Creep. Swelling. Irradiation enhanced segregation, crack propagation and embrittlement. Irradiation assisted corrosion and environmental degradation. Effects of helium. Joining and interface technology.	Corrosion-oxidation. Irradiation damage. Joining and interface technology. Environmentally assisted cracking Radiolytically induced degradation
Key methods for solution of problems	Modelling and its validation. Advanced materials characterisation. Advanced measurement and testing techniques. Advanced plant monitoring techniques	Modelling and its validation. Advanced materials characterisation. Proxy irradiation (e.g. ion beams). Advanced measurement and testing techniques. Advanced plant monitoring techniques	Modelling and its validation. Advanced materials characterisation. Advanced measurement and testing techniques. Advanced plant monitoring techniques
Most promising immediate opportunities	Modelling validated by microscopic characterisation, plant service data and long-term experiments. Exploit research synergies for fission, fusion and fossil-fuel plant materials.	Modelling validated by microscopic characterisation, proxy irradiations, plant service data and long-term experiments. Exploit research synergies for fission and fusion plant materials.	Modelling validated by microscopic characterisation, plant service data and long-term experiments.
Key gaps in capabilities	Lack of creep-fatigue testing facilities. Lack of irradiation facilities	Lack of irradiation facilities.	Autoclaves for corrosion testing and the study of environmentally assisted crack growth. Archived materials from surveillance and decommissioning. Lack of irradiation facilities
Components	Primary and secondary circuit in LWRs, advanced reactors and fusion. Near core components in AGRs. Divertors and blankets in fusion.	In core components in AGRs, LWRs, advanced reactors. Blankets and divertors in fusion	Components within chemical plants Materials/components in storage before reprocessing. Waste packages Cabling and sensors

It clearly makes no sense to mount a UK programme to address all these issues. The existing Core Competencies in the UK are particularly strong in the areas of materials characterisation, mechanistic understanding of failure processes, and materials modelling. Four critical issues are identified as Next Steps that can be addressed effectively by UK researchers. These critical issues have been selected because their resolution will advance immediate UK strategic interests, and play to UK strengths. Although each of these programmes is primarily focussed on a sub-set of issues and materials, they would contribute to all three of the columns in the preceding Table.

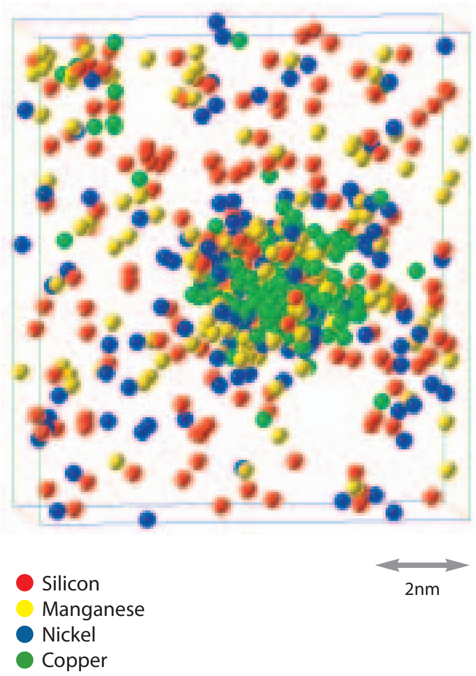
A Understanding the mechanisms of in-service and in-repository corrosion and degradation of materials such as austenitic and ferritic steels, cements, glasses and polymers, taking account of the total environment. This would combine expertise and interests in academia, industry and government research organisations.

B Fabrication techniques (such as welding or pre-service surface treatments) may have an impact on in-service performance that is not well understood. A research programme should be focussed on predicting the behaviour of welded structures subjected to high temperatures and complex loading during service. There is a potentially valuable link to materials for advanced fossil-fuel plants.

C A fission-fusion materials research programme aimed at irradiation damage issues, to underwrite longer term operation of plants. This would exploit synergies arising from the common problems, common experimental and theoretical methods of investigation and the overlap of key materials, and would take advantage of recent major advances in research methods.

D Non-destructive methods are used to underwrite installed plant integrity by ensuring that any flaws are within the design specification. Inspections are also undertaken at regular intervals over the service life via prescribed maintenance schedules. Research is required on these technologies as greater demand is placed upon inspections. Many other potential changes to material performance arise from the total service environment. Traditionally, tools such as installed surveillance samples, selective removal of material for examination and testing, corrosion monitoring, etc. have been used. There is a need to develop the ability to monitor changes on-line and define safe limits. Requirements range from improved quantitative measurement of microstructural change, to enhanced image analysis and information recovery, and the use of smart materials that can be installed within critical regions.

It should be noted that these programmes are multidisciplinary in nature, requiring the investigation of a wide variety of issues, ranging from stress analysis in large scale structures to the effects of coolant chemistry on corrosion behaviour. It will be necessary to link together academia, research organisations and industry in order to achieve maximum benefits from this research.



Atom map showing the presence of a 3nm irradiation induced cluster containing copper, manganese, nickel and silicon atoms in a reactor pressure vessel steel.
[Courtesy of Nexia Solutions Ltd]

6.0

Key barriers to progress

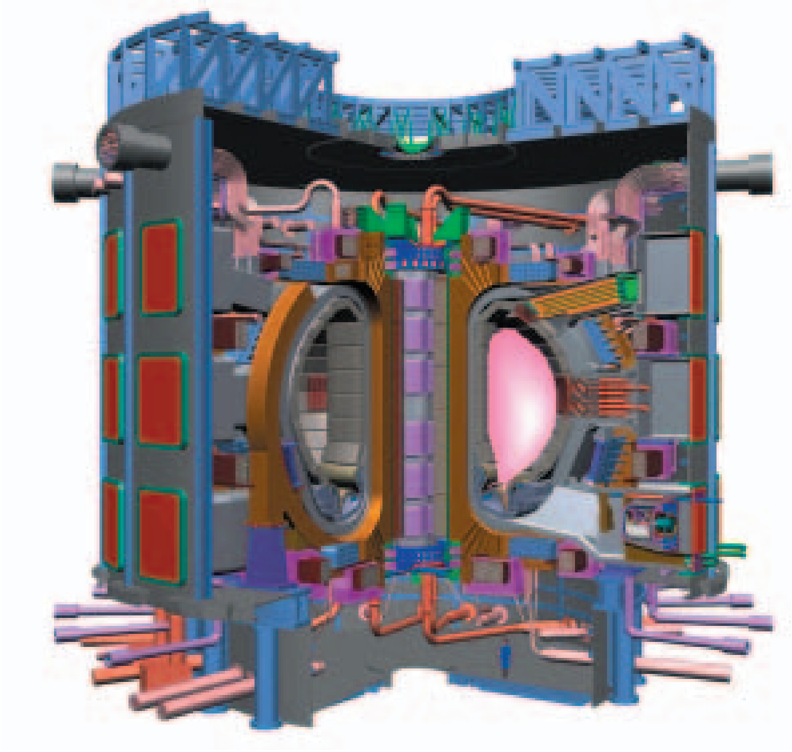
Currently, in the UK, the prime barriers to the successful execution of productive research in the fission field relate to resources; financial, human and physical.

In the fission industry, lack of confidence in the stability of future regulatory regimes (licensing and planning; and fiscal/financial instruments designed to suppress climate changing emissions from other sources) has produced artificially high risk premiums for the construction of new fission power plants and extensions of the operations of existing plants, and so has severely suppressed (to very low levels) the commercially-funded research that might otherwise have developed in response to financial signals such as the price of carbon. This perception is not likely to change rapidly. Publicly-funded research has not filled the gap left by this market failure, being also at very low levels with little continuity or stability.

The UK skills base in these areas is in urgent need of refreshment. The volume of available expertise has been declining for many years, and is dispersed among many institutions. There is little effective contact with global research and information networks, which themselves have generally suffered comparable declines.
The availability of facilities in the UK for irradiating and examining materials for the experimental validation of understanding and modelling has been in steep decline, in parallel with similar declines throughout much of the world. Only limited arrangements have been put in place for the effective sharing of access to the world's limited facilities or for pooling of related research programmes. In particular, it is difficult to arrange for material to be irradiated in facilities outside the U.K., especially when longer-term studies of properties such as radiation-assisted creep and creep-fatigue interactions are required. Assured access to such facilities (including materials test reactors) and to equipment for the examination of radioactive samples, is essential. Any future strategy must also make the best possible use of the capabilities within front-line university material departments. Organisations such as the proposed National Nuclear Laboratory have a key role to play, and it is important that their facilities should be made available to outside researchers. The exploitation of synergies with the fusion materials research programmes is also essential (see below).

The situation is rather different for fusion materials research. Though there is no commercially-funded research, and the UK publicly-funded research programme is small, in other respects it is in better shape. Funding is stable, and there is a unifying core of research activities in one institution (Culham), in close interaction with a penumbra of related work in leading UK universities and RTOs, and forming an integral part of a coordinated European programme which includes access to irradiation facilities. A major projected international fusion materials irradiation facility - IFMIF - would be of wide benefit if located in the UK. Though fusion and fission are very different in many respects, there are very substantial commonalities in the materials areas, and major potential benefits could be obtained in both fields from the exploitation of common research programmes.

It is worth noting that the Stern Review [4] concluded that the economics of climate change and its mitigation mandate at least a doubling of rates of expenditure on energy research, specifically citing (on page 363) energy materials as one of four priorities for scientific progress.



A cutaway drawing of the core of a 600 Megawatt fusion device, ITER, which is beginning construction in France. The partners in ITER are Europe, Japan, China, India, Russia, Korea and USA. Although fusion and fission power plants are different in many respects, there is a large overlap in the classes of materials they employ, the effects that limit the lifetime of materials, and the research methods used to gain the understanding needed to optimise materials performance.

7.0 Recommendations

1 The focus of the research agenda should be confined to areas specifically addressing UK needs and opportunities, using UK strengths, but effectively linked to European and global research and information networks and experimental facilities.

2 Four immediate promising opportunities have been identified that play to the strengths of UK Core Competencies and would yield substantial progress on key cross-cutting issues. These opportunities arise because of the existence of synergies in experimental and modelling techniques. Accordingly, it is recommended that new or enhanced multi-disciplinary research programmes, integrated across the whole of the supply chain, should be launched into:

- mechanisms of in-service and in-repository corrosion and degradation of materials;
- predicting the behaviour of welded structures subjected to high temperatures and complex loadings;
- predicting irradiation damage effects in fission and fusion materials;
- development of new and improved methods for non-destructive monitoring and evaluation of materials in service.

3 Stability in funding is essential, as is ‘ownership’ of the Strategic Research Agenda by a consortium of key institutions, accompanied by clear leadership and direction, and drawing in the expertise and resources of industry, research institutes, universities, regional development agencies, the proposed National Nuclear Laboratory, etc..

4 Initially, the strategic research programme should be developed by exploiting existing Core Competencies in the UK and harnessing them in multi-disciplinary Flexible Teams that can be focussed on the critical problems and issues. At a later stage, a case for further development of Core Competencies can be made.

5 The research should be reciprocally linked to skill base refreshment to develop and retain expertise and knowledge. Research that uses the UK inventory of pertinent skills and data is one of the most effective ways - perhaps the most effective way - to maintain/refresh such UK assets.

6 A national knowledge management capability is required to ensure that maximum benefit is obtained, both from existing knowledge and from that generated during future research

7 The fission and fusion materials research needs to be linked to other areas where synergy can be exploited, especially to materials for advanced fossil-fuel power plants. There would be major benefits to the UK if the planned international fusion materials irradiation facility (IFMIF) were located here, and every effort should be made to bid for it if the opportunity arises.

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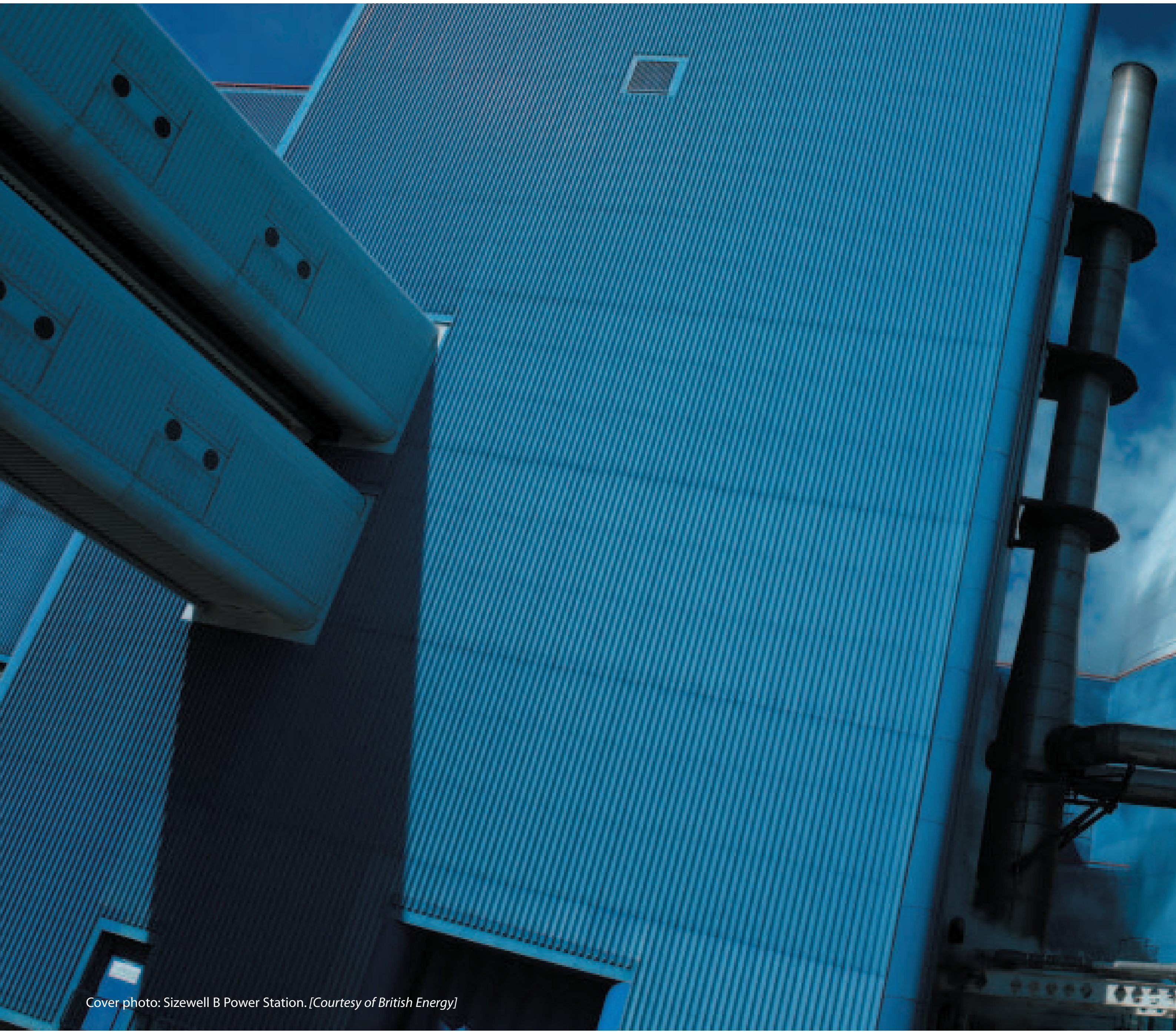
Cover photo: Sizewell B Power Station. *[Courtesy of British Energy]*

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