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EPSRC Independent Review of Fission and Fusion

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1. Executive Summary

- In a global context of increasing demand for energy, security of supply combined with pressure to decarbonize the energy supply will require that nuclear fission play an important part in the world energy mix over the next decades. The UK has a stated policy of encouraging new nuclear build, and a decade of effort has rebuilt research capacity in the UK. EPSRC's priorities must now be built within the context of Government's policy actions. The panel has, therefore, recommended alternative strategies.
- The current magnetic confinement fusion programme in UK is of world-class quality, in facilities, people and impact, while UK also hosts a strong community carrying out research relevant to inertial confinement fusion. Nuclear fusion remains a long-term goal, important as the highest energy density technology with the lowest conceivable footprint. The panel recommends a timeline for the check-pointing of current fusion projects.
- We stress the need for a stable agenda on a decadal time scale.

Fission research

- In fission research, the effort over the last decade to rebuild a coherent research community from the very low base to which it had been allowed to fall has had some success, thanks to EPSRC investments together with investments from other public bodies (e.g. Nuclear Decommissioning Authority, NDA), good links with industry and developing technology transfer.
- There are now some areas in which the UK is at least internationally competitive, and the next step should be to take the opportunity to focus and develop a strategy in fission research to achieve more international excellence.
- Though outside the remit of the EPSRC the broader landscape of advice and oversight to government in this area is complex and confusing, which the panel recommends should be simplified for accountability and transparency.
- There are substantial potential policy uncertainties, which hamper the development of a research strategy on the basis of national need. Nonetheless, work needs to proceed to develop a strategy that mitigates the risks of the different possible policy developments and outcomes, and maintains the capacity to seize opportunities in support of potential new initiatives (for example, a decision being made to rapidly develop small modular reactors or a new Generation IV design).
- Whatever policy developments might be anticipated, the necessity for continued work to implement safe, cost-effective decommissioning, clean-up and waste disposal of existing nuclear sites and facilities is a given. There are substantial opportunities for new science and technology developments in this area, the

existing research community is strong and in some aspects internationally leading, and the national importance and potential impact of this work is high. There is a substantial societal dimension to the work, and due attention needs to be paid to the need for cross-council working with other relevant Research Councils such as the Natural Environment Research Council (NERC) and the Economic and Social Research Council (ESRC).

- The direction of research required to support nuclear new build remains uncertain until national policy is clarified. Whatever the outcome of that policy discussion (and we took note of the recommendations of the Nuclear Innovation and Research Advisory Board (NIRAB), which would have broad implications if adopted) there is an important science agenda to be pursued which needs to consider the whole cycle. The urgency of the situation is underlined by the aging work force and the consequent possibility of losing important knowledge through retirement.
- Three key underpinning science areas, in which the UK does have internationally competitive work, are advanced fuels, materials science, and modelling (both of materials and of systems). Fundamental research in these areas could enable breakthroughs to enhance reliability, environmental attractiveness (e.g. less waste), operational safety, and economics of future reactors.
- The science and technology that underlies the programme of life extension for the existing Advanced Gas-cooled Reactor (AGR) fleet is challenging and scientifically interesting, and some good expertise has been developed in this area. Given the short-term nature of this challenge, thought needs to be given to the proper distribution of the cost of necessary research between EPSRC, other government agencies, and the private sector operator of these plants.

Fusion research

- The UK's programme of magnetic confinement fusion (MCF) has a high degree of scientific excellence and is currently central to the wider international effort in MCF.
- The JET (Joint European Torus) programme is of the highest level of international importance, as the only tokomak able to run D-T experiments (Deuterium-Tritium). Its results are vital for mitigating risks at ITER (International Thermonuclear Experimental Reactor). We recommend a review of the future of the JET programme about two years after the D-T experiments re-start, namely about 5 years from now.
- The recent capital investment in MAST-U (Mega Amp Spherical Tokamak Upgrade) will result in a facility that is world-leading in its particular design space, and which allows flexible high quality science. A checkpoint for MAST-U should occur about a decade from now.
- The university research community is well integrated with the national programme at the Culham Centre for Fusion Energy (CCFE), and has particular strengths in modeling.
- Other areas supporting the MCF programme – such as materials for fusion (discussed below), and the development and transfer of remote handling

technology, are very valuable and should be considered in a wider context than fusion alone.

- It makes strategic and scientific sense to develop CCFE's power plant design capability, but this is a long term aspiration.
- The UK's activity in inertial confinement fusion builds on a relatively small community, scientifically excellent in niche areas, in high energy, high density plasmas and plasma/laser interactions. This work has national security implications and provides valued input into much larger overseas programmes, particularly the National Ignition Facility (NIF). This is currently appropriately supported, for example through the Plasma and Lasers research area.

Research underpinning both fission and fusion

- Research into materials in the UK is very strong; there is complementarity between materials requirements for fission and for fusion and there is evidence that those synergies are already being recognized and exploited. Investments in the fission programme have pulled in researchers from materials science who had not previously had nuclear experience. This is very positive and leverages existing UK strengths in the broader field of materials science. The materials science research to understand mechanistic behavior and to design high performance materials that will reliably function in these extreme operating conditions is both scientifically challenging and of high industrial importance. Research and development on manufacturability and new manufacturing technologies needs to be integrated into materials research.
- Remote handling is a required capability to support the nuclear mission, both in fission and fusion. These capabilities develop skills and expertise that are commercially relevant in many areas.

International links

- International collaborations are seen as being particularly important for academics, allowing access to complementary facilities unavailable in the UK and the exchange of specific UK areas of competence (e.g. modeling). There are several excellent current examples of UK international collaborations in the area of fission and fusion materials research that provide important amplification of EPSRC funding. International collaboration has wider importance for UK plc in building key relationships. The panel recognizes the administrative burden of some of these programmes and thought should be given to ways to streamline participation in these collaborative programs.

Training and People

- The panel recognized the success of the Centres for Doctoral Training (CDTs) in creating a pipeline of people with a breadth and mix of skills and capabilities that are clearly widely valued both inside and outside academia. It will be important in the future to ensure that CDTs need to be balanced with a strong and vibrant research programme aligned with national research priorities, and that well-defined career paths emerge in a rejuvenated nuclear industry to provide rewarding careers for this new cadre of talented individuals.

2. Fission

a. Overview of fission research in the UK

The past decade of investment by EPSRC and other UK public funding bodies in the UK's nuclear future has seen significant progress in building a research community in nuclear fission, albeit from a very low base. Research activities span the broad areas of waste, decommissioning, fuels, materials, and systems. Several world-class experimental facilities and a National Laboratory network have been created, in particular for evaluation of materials. There are significant international partnerships, especially with Europe, India, Japan, Korea, and the USA. The community has drawn in researchers from non-nuclear research backgrounds, especially in materials sciences, geosciences, and modelling. Several new groups have attained international stature for their research. The community is cohesive, though still modest in size, and connections between academia and industry are strong, evidenced by jointly funded research, student and training engagements, and career placements of students into the industry.

The immediate research needs of the nuclear industry are met by research carried out 'in house' or procured from specialist technical organisations. EPSRC research has a valuable role in complementing this industrial research, progressing 'blue skies' research, providing scientific underpinning and pursuing innovation with potential for step changes in technology.

It also has a vital role to play in providing a well-educated, skilled nuclear workforce which can deliver the UK's energy demands and provide growth for the UK economy.

We note that the recent progress has led to an unwieldy proliferation of advisory boards (outside EPSRC's space but overlapping it), oversight committees, and reporting structures, with a corresponding lack of clarity of ownership. Whilst noting that this is outside of the remit of EPSRC we believe there is scope within the sector to simplify these structures to improve accountability.

Recent provision of new research facilities is important and welcome, but capital expenditure should be balanced by planned support of research activities within those facilities.

The research portfolio that has emerged is diverse and reflects the natural outcome of a period of rejuvenation. It is an opportune time to focus and prioritise efforts around a strategy for the research that supports national goals for the UK's nuclear future. EPSRC is responsible for maintaining a core capability to support nuclear sciences, but the directions to be developed within that portfolio should support a national strategy. Since a long-term national strategy has not been entirely decided, our report will recommend a priority on research areas which are critical for the UK (waste management and decommissioning) and on activities of UK strength which will be important under many or all future scenarios (materials, fuels, reactor engineering, and

modelling). We also recommend that strategies be developed to support three plausible scenarios in the medium term:

- Support to roll-out of a new large Light Water Reactor (LWR) fleet
- Support to development and commercialisation of a 'conventional' light water Small Modular Reactor (SMR)
- Support to development and eventual commercialisation of a GenIV high temperature SMR

b. Priorities for fission research

Context

Over the next 10-15 years the UK energy sector is faced with 3 major issues in nuclear fission:

- Decommissioning of existing facilities and management of the arising wastes - both fuel and other active materials
- Implementing a major new build programme - currently focused on up to 16 GW of new capacity of Gen III+ LWR technologies
- Maximising the valuable life of the existing fleet of 7 AGR plants - recognising that all of these are currently scheduled to close by 2023 but that life extensions to 2028 are being considered for at least 1 plant (Hinkley Point B)

Decommissioning

There is general agreement that decommissioning is an immediate and pressing need and that the UK has world leading academic and industry capabilities in materials handling and reprocessing. The panel agreed that priority should be given to creating increased value from science, technology and engineering support to this area.

Key science opportunities lie in improved fundamentals and application of surface chemistry and materials separation.

Engineering issues relate particularly to remote handling of materials and structures and the civil engineering and geotechnical aspects of access to large, aging structures with large plant whilst minimising local ground disturbance and impact on other structures. Much of the science and technology in this area has applications in other sectors and the strong 'Remote Access in Challenging Environments capability developed under the CCFE fusion grant programme at Culham is demonstrating this. Increased opportunities should be sought to apply this capability into the fission arena as a priority.

Waste management and geological disposal are considered important elements to support both decommissioning of the existing AGR fleet (and many other legacy facilities) and any future new build programme. Some issues associated with geological storage in the UK are related to societal engagement rather than being constrained by a fundamental lack of technology. Where there are technological issues they appear to

lie at what is currently seen as the EPSRC-NERC interface (ground water flow management for instance) and increased linkages may prove beneficial. In this context increased engagement with NERC and ESRC could offer increased value.

New Build

The UK new build programme of large scale LWRs is running behind the anticipated schedule and, currently, there is no clarity on the exact timing or delivery rate for new plants. The UK Government target is for 50% of the plants' content to be sourced within the UK and this is expected to include civil engineering works and fuel supply. Other elements will come from a range of international suppliers. Expectations are that between 1 and 4 plants could be built to 2030.

Part of the uncertainty in delivery is created by the financing costs for these very large plants. In some cases this challenge is increased further by the risk factor applied to capital supply based on real and perceived technical delivery issues with build of comparable designs elsewhere in the world. The challenge of finalising capital supply is the key issue delaying start of new build in the UK. However, if this can be resolved (and progress on financing the first plant is being made at the time of this report), it is clear that deployment of large reactors will be a priority for the UK Government over the next 15 years.

One consequence of this capital provision uncertainty is a growing interest in lower capital cost SMR designs (ranging from 10-200MW vs 1000MW+ for the large LWR plants). These units are not yet demonstrated but are increasingly viewed as achievable and deliverable as demonstrators within 10 years. Designs cover both current technology systems and Gen IV high temperature systems. Pursuing demonstration of SMRs would require considerable science and technology support in reactor system design, associated power generating systems, materials science for fuels and structural materials and advanced manufacturing for volume manufacture of quality components at low cost. Delivery of an SMR demonstration and commercialisation will require strong industry leadership which is not yet in place. Further, industry and commercial priorities, rather than scientific excellence, will decide the technical content and system design which will be based on global market opportunities.

Whilst the UK opportunity remains uncertain (large LWRs, 'conventional technology' SMR, high temperature SMR) it is clear that there will be a need for science and technology support to any or all of these routes. The focus for support and the appropriate funding level will be different in each case and the strong community which has developed under the last 10 years of EPSRC support are best placed to articulate the various opportunities and needs.

Recognising these uncertainties, the panel recommend that the UK academic fission community are tasked with developing 3 fission science and technology strategies:

1. Support to roll-out of a new large LWR fleet
2. Support to development and commercialisation of a 'conventional' light water SMR
3. Support to development and eventual commercialisation of a GenIV high temperature SMR

Constructing these 3 strategies now – we envisage at this stage scoping studies, not full programs – will aid in mitigating the risk of assuming any one route or technology is optimum and should provide a platform for driving integration of efforts in the event that more than one option actually results. There are synergies and commonalities across materials science, fuel technology and modelling in all three cases for instance and these should be exploited. The issues, needs and opportunities raised under decommissioning (above) should also be considered in the context of these strategies.

It should also be recognised that there is an unlikely, but real, possibility that no new build programme is established in the UK at which point the value of continuing fission support in any areas other than decommissioning in the short term, and Gen IV in the long term, should be re-considered.

Plant Life Extension

The panel heard varying views on the level of necessary science support and timing of potential AGR plant life extensions. Extension increases security of supply across the UK system and defers the need for new asset investments. However, whilst the opportunity to extend asset life is clearly valuable (stated by one interviewee as up to £1m per day of additional life), it is driven primarily by the commercial investment case for the operator (EDF). In this context the panel recommend that the case for EPSRC support to projects supporting plant life extension is considered in discussion with the commercial operator and any other potential funders.

It was noted that the UK has strong expertise around the materials and structural integrity technologies associated with the specifics of the UK AGR fleet including a world-leading capability around graphite structural performance and damage development. These are aspects which could be important in development (globally) of any GenIV (high temperature) SMRs.

Fission research facilities

There is a concern raised by many interviewees that whilst there has been a highly valued investment in key experimental facilities over the last 10 years (particularly through the National Nuclear User Facility, NNUF, and the National Nuclear Laboratory, NNL) there has not been an aligned commitment to provide additional resource support.

Further, many of the facilities have been established on the basis of being 'commercial' units meaning that access for academics (charged at 'full' cost) is considered too expensive compared to use of comparable facilities in mainland Europe which generally operate on recovery of marginal costs only. This situation is compounded by some key NNL facilities (materials Post Irradiation Examination for instance) being embedded within the Sellafield licensed site which brings an additional overhead burden around security and safety.

It was noted that recent EU awards have reduced the placement time on EU facilities from 12 months to 3 months with consequent limitations on the scale of project which can be carried out. It is expected that this, combined with the challenge of accessing NNL facilities, will reduce the effectiveness of delivering key projects where active materials evaluation is key.

The establishment of 'intermediary' active facilities, such as the new materials facility at CCFE for irradiated materials evaluation, are viewed as high value to the academic community as mitigation to these challenges.

The panel heard from NIRAB on their recommendations for a further £250M investment in future fuels (accident tolerant systems), improved manufacturing, GenIV reactor design technology and cost effective / sustainable recycling. If funding is provided by government to take these recommendations forward the panel strongly recommend that an integrated approach is taken to funding facilities and resources and that the costing approaches are developed on the basis of enabling and incentivising (rather than effectively dissuading) academic engagement.

Similarly, linkages and integration with the Sir Henry Royce Institute for Materials Research and Innovation and their research on materials systems for demanding environments should be strengthened and synergies sought to ensure there is no duplication and cross-sector learnings are maximised.

Materials

The UK has a very strong research community in materials broadly (including materials modelling) and this has translated into a recent resurgence of powerful research activities in materials for fission and fusion. This ascension to internationally competitive stature in materials for fission and fusion has leveraged outstanding baseline competency in UK materials research (particularly advanced microstructural/nanoscale characterization and modeling) along with selected investments in specialized facilities such as ion accelerators to efficiently investigate fundamental aspects of radiation damage; it is remarkable that the UK has achieved a favourable international reputation in fission and fusion materials research without access to a materials test reactor.

Under all conceivable scenarios for nuclear new build, materials expertise is a required underlying capability. In both fission and fusion, there is a strong need for fundamental

research on materials in extreme conditions, radiation damage mechanisms, corrosion, advanced joining methodologies, and deformation and fracture phenomena including stress-corrosion cracking and creep-fatigue processes. It would be beneficial to exploit latent “materials by design” capabilities to create a new suite of improved performance materials specifically tailored for the demanding fission/fusion environments. For SMR scenarios, advanced manufacturing methods amenable to process-based qualification will be essential to achieve desired economics. For both the large LWR fleet and light water SMR scenarios, emerging innovations such as accident tolerant fuel systems may provide enhanced safety (e.g., additional coping time in response to loss of coolant) as well as the potential to enable deeper fuel burnup which would improve fuel utilization, economics, and reduce waste disposition burdens. Finally, development of remote handling innovations would be beneficial for fission and fusion reactor maintenance as well as decommissioning operations.

While detailed applications may vary between the fields of fission and fusion, the underlying science is often common and we recommend that this portfolio be considered as one. Emerging needs from fusion research should tap into the present expertise in fission. We see the development of a NNUF across several sites as a good way to cement the research community and sponsor innovative pathways. There are increasing opportunities to incorporate atomistic modelling and experimental nanoscience tools into the design of materials and fuels as well as their manufacture.

International Partnerships

International partnerships, especially with EU, India, Japan, Korea and the US, were highly valued by UK academics who participated. They praised the intellectual level of their partners, the opportunities to upskill and learn unfamiliar research areas, the access to international facilities that offer resources unavailable in the UK, and opportunities for students and early career researchers to gain global experience. The collaborators also value highly their interactions with the UK scientists and the access to the facilities in the UK. Industrial representatives were more circumspect, perhaps because they had less involvement and different drivers, though all recognize the value that the key relationships bring to the UK enterprise.

Fission research is currently largely supported by bilateral partnerships, and fusion by multilateral partnerships. This is appropriate given the timescale - but we note that advanced reactor research may also be appropriately served by a multilateral partnership with a 30 year horizon.

We recognise the considerable administrative burden for EPSRC to support and resource these partnerships under the current model of multiple calls that end up with the support of multiple small grants. Simplification would reduce the administrative burden, and potential advantages could include a more strategic view of bilateral

collaborations, and more formally bringing in industry partners, both UK and international.

3. Fusion:

a. Overview of Magnetic Fusion Research in the UK

Today's fusion energy research programme in the UK is a product of a long and distinguished history of achievement in this field. The UK has been a key player in establishing the foundations of fusion energy, beginning in the 1950s. In particular, it has developed international excellence in plasma physics that underlies fusion energy, with deep expertise in experimental and theoretical science. Recently, UK expertise has been expanding into areas of fusion technology and materials science – a wise development as fusion progresses toward the goal of energy production.

The current programme is of world-class quality, in facilities, people, and impact. The national program is a tightly knit, well-integrated effort. The central effort resides at the Culham Centre for Fusion Energy (CCFE), complemented by a strong university programme. This integrated program is appropriately broad topically, strongly coupled to international partners, and supported by a very effective Centre for Doctoral Training in fusion energy.

CCFE operates two major experimental facilities and has recently grown efforts in materials, remote handling, and integrated fusion system design. The centre occupies a special and central role worldwide in that it hosts the JET facility. JET is an essential, unique experiment that the world fusion community relies upon for information that is crucial to the upcoming ITER project. JET is the only experiment that can operate with the fusion fuel of tritium and deuterium. It is needed to provide new data on plasma behaviour with fusion fuel, which will influence how ITER is operated and provide crucial training in the engineering operation of such a facility. In addition, JET now operates with a surrounding material boundary that is identical to that planned for ITER (the "ITER-like wall"). It is imperative that an understanding of the influence of the ITER-like wall on plasma behaviour be obtained. Extrapolation of new information from JET to ITER is aided by the strong geometrical similarity (plasma shapes) between the two facilities. The new information obtained on JET will have large effect on the success of ITER – such tests on ITER itself would be enormously more time-consuming and costly. Furthermore, the JET results are of importance beyond ITER and to fusion in general.

The second facility at CCFE – the MAST-Upgrade – is a medium-sized experimental facility that is the best-in-class worldwide of the fusion plasma configuration known as the spherical tokamak. MAST-U, and a sister facility in the US, lead the world in this approach to fusion. MAST is nearing completion of an upgrade (to MAST-U) that will greatly expand the scientific capability of the facility. When it begins operation, it will

essentially be a new fusion facility that will: explore a possibly more compact approach to fusion energy, develop novel solutions to the crucial challenge of the plasma-material interface, and provide results of importance to ITER and plasma confinement science. As a flexible research facility, MAST-U will attract researchers internationally (as well as from UK universities). It will be a scientifically robust facility for ten years and more.

The CCFE programme has new efforts in materials, remote handling and fusion system design. These three new elements are wisely chosen with a view toward the long-term leadership of the UK fusion program. Material challenges are severe for fusion, scientifically synergistic with fission needs, and must be overcome for fusion to succeed; remote handling is essential for fusion systems, with applications to many hazardous environments other than fusion; integrated systems design is crucial to guide fusion research and plan for the DEMO facility.

The two major facilities, complemented by the three new initiatives, place CCFE clearly at the world forefront in fusion. The strategic activities are important at present and key to positioning the UK for a leadership position after JET completes its mission. The CCFE effort is enormously cost-effective due to the strong financial leveraging from the EU through its contributions to JET. The UK gains a benefit from JET that is disproportionate to its investment through its large physicist participation and its responsibility for JET operations.

The university programme is key to the UK fusion effort – for the scientific depth and innovation that it brings, for the links that it establishes between fusion and other areas of science and, of course, for the training of the fusion workforce. In recent years, the university fusion activities have strengthened, with notably powerful programmes (e.g., at York, Warwick, Oxford, Imperial College and others). Universities bring many core capabilities, such as theory and integrated simulation, the science of the plasma-material interaction, diagnostics, and links to low temperature plasma physics, plasma astrophysics, and complex systems.

The UK fusion programme, in sum, is world-leading, well-structured, lean, and cost-effective. The UK strategy for fusion, expressed through the program activities, brings strong benefits to the UK, while being intimately woven into the international effort. It is a program with no apparent, major weak links.

b. Priority for Fusion Research Elements

The UK fusion programme can be considered to have six program elements: five at CCFE and the university programme (which itself has multiple components). All six elements are scientifically or technologically strong, needed for fusion, and well-justified. Below, we comment on the CCFE programme elements in priority order. However, all elements are strong and contribute to a coherent, balanced program. Finally, we describe the university programme which is essential for a healthy national programme.

1. JET

JET is a central facility for the world, is unique in its D-T capability and ITER-like wall, is crucial for ITER, and is strongly leveraged financially. The UK has a responsibility to operate JET for the international community, from which the UK gains tremendous scientific advantage. JET is an absolutely essential component of the UK programme. Within 2-3 years after the DT operation restarts, JET should be reviewed on the basis of its continued contribution to international programs.

2. MAST-Upgrade

MAST-U will soon (in about 1.5 years) complete its construction. It will be the experimental centrepiece of the UK domestic programme (considering that JET is a European facility), guaranteeing the scientific vitality of the CCFE programme for at least a decade. It will be the newest fusion facility in the UK, ready to reap the benefits of a substantial investment in its construction. It is an absolutely essential component of the UK programme. As described above, MAST-U will develop a relatively compact approach to fusion, develop new solutions to the plasma-material interface, and advance physics for ITER and beyond. A natural time for a checkpoint review of MAST-U would be in about a decade.

3. Materials for fusion and non-fusion applications

Recently, a new materials activity has been initiated, including a group with expertise in nuclear materials and the new Materials Research Facility (which will be able to test irradiated materials and is part of the National Nuclear Users Facility). The challenge of materials in the extreme fusion neutron environment is severe and under-researched to date. It is impressive that CCFE has ramped up an expert group that is making significant contributions. There is a strong attempt to drive an active and robust synergy between fusion and fission materials research. This can place the UK on a track to be in a world-leading position in nuclear materials. Materials for fusion is surely an increasing area of research importance. It is an extremely wise move for CCFE to establish this new capability.

4. Remote handling for nuclear and non-nuclear markets

CCFE has recently established a new activity in robotics and autonomous systems. This is clearly needed for upcoming fusion systems, and exploits the substantial experience gained in JET. In addition, it is an area with economic benefit to the UK – the activity has already helped UK industry to win £100M of contracts for ITER. CCFE anticipates that their research in this area will continue to reap substantially more such contracts for other applications. Remote handling is a very targeted capability, important for fusion, although not key to the scientific foundation for fusion. Remote handling is of course a key enabler for decommissioning of nuclear facilities, and is also of relevance in any situation where there are chemical, radiological, or biological hazards. Consequently, the UK capability in this area carries substantial economic

benefit and may place the UK in the position of being the provider of such services for fusion and beyond. In some sense, it is an activity that might well more than "pay for itself."

5. Integrated fusion design

CCFE is gathering a capability in integrated fusion system design, from plasmas to neutronics to magnets. It aims to establish a Design Centre that could play a central role in the EU DEMO design (DEMOnstration power plant). A fusion system is complex and integrated. Such a design centre capability is essential to move beyond ITER to DEMO. It is also essential to guide fusion research (e.g., pointing to areas where physics advance can have large practical impact) and to vet various approaches to fusion (new ideas cannot be evaluated without understanding the whole system). The new Centre is aimed to position the UK to be a key player in the post-JET, post-ITER future.

The University Programme

The university programme is strong and well-integrated – key to the scientific health of the field as well as training the workforce. In recent years, university programmes have strengthened in fusion and plasma physics – thanks to targeted, funded training programmes as well as individual university investments. The university programme is an absolutely essential component of the UK fusion effort. The current level of effort is likely the minimum needed to support a robust national effort in fusion energy.

International Partnerships

The fusion activity is highly globalized and internationally collaborative. This has been a hallmark of the fusion program since its inception - throughout the cold war, Soviet and western scientists worked shoulder-to-shoulder. The UK is strongly partnered internationally in fusion research. Clearly, its participation in ITER is an unprecedented example of scientific partnership. Similarly, JET is explicitly an EU facility. But, the UK is strongly partnered internationally well beyond these two major facilities. MAST-U has a large number of international "users," and it coordinates its program with its sister facility in the US. And beyond facility partnerships, the broad research effort involves scientist-to-scientist collaborations at all levels.

IFE Fusion

The UK hosts a strong community in High Energy Density Physics supported by research facilities at AWE (Orion) and RAL (Vulcan) which is relevant to Inertial Confinement Fusion. Research support for the community through EPSRC is largely through the plasmas and lasers research area. This community is performing world class science, particularly in the interaction of strong fields with materials, and they are already contributing to research at NIF. We recommend that the research focus should be on targeted contributions to NIF and to LMJ (Laser Megajoule) as it comes on line.

3. Training

Doctoral training in both fission and fusion is focused on Centres for Doctoral training (CDTs). These provide funding to students for four years and include training in technical and transferrable skills, as well as a research element. There are two CDTs in fission, Next Generation Nuclear, involving the Universities of Manchester, Lancaster, Leeds, Liverpool and Sheffield and Nuclear Energy: Building UK Civil Nuclear Skills for Global Markets, involving Imperial College, Cambridge and the Open University. The Manchester-led CDT followed an earlier award from 2009, whilst the award to Imperial established a new centre.

In fusion, the CDT in the Science and Technology of Fusion Energy involves University of York, University of Durham, University of Liverpool, University of Manchester and University of Oxford and again follows an earlier award.

All the CDTs reported a high demand for their courses with up to 10 applicants per place, enabling recruitment of a high calibre of student. Students came from a wide variety of backgrounds, with a significant representation of mid-career scientists with several years' industrial experience as well as recent graduates. Research carried out in CDTs was generally of a high standard.

The CDTs benefitted from strong industrial involvement, both in contributions to teaching and in co-funding and supervision of research. This flexibility was viewed as particularly attractive as it helped to support students from a less traditional background, contributing to high standards and diversity. Students said that they found the CDT format particularly attractive and welcomed the opportunities for learning from teaching as well as from research as well being part of a cohort, rather than an individual.

CDTs which had been established for sufficient time for students to progress to course completion reported a very high transfer rate to careers in the technology area. For one of the fission CDTs, 30 of the 33 course graduates had continued in academic or industrial research in the field.

EPSRC provides the same level of financial support for PhD training through the Doctoral Training Partnership (DTP) and Industrial CASE awards (ICASE), as it does for CDTs. There was some criticism, principally from those who were not directly involved, that the CDT model focussed investment in a small number of institutions and thus disadvantaged the remainder. However, on balance the Review Panel considered that the benefits of the CDTs outweighed the disadvantages and that the mechanism provided an effective route for provision of graduate training in fission and fusion. Other training opportunities (DTP and ICASE) are, and should continue to be, available alongside CDTs as these provide a diversity mechanism to retain specialist niche expertise in other institutions.

Representatives of industry reported that they were now starting to see a good pipeline of well-qualified students applying for technical opportunities within their businesses. They considered that this was a direct consequence of the significant investment in nuclear training and research made by the EPSRC during the last 10 years or so. However, continued investment was considered essential, particularly to meet an increasing demand for new nuclear capability over the next decade to refresh a workforce where a significant proportion will be retiring within this period. If a new generation of nuclear power plants were to be built in this time period, this would place additional requirements on nuclear skills.

4. Conclusion

We conclude with a list of our major findings and recommendations.

- The UK has rebuilt research capability in fission research, and has the capability to be a major player. Training capability (particularly through the Centres for Doctoral Training) is strong. The connection to, and pull from, industry is excellent.
- Research priorities for fission should be determined in the context of long-term national goals for the deployment of fission energy, not all of which have been established. It would be prudent therefore to be ready for several scenarios, and we outline three: support for new build; research for Small Modular Reactors; research for generation IV. We consider that support for research relevant to decommissioning is obligatory.
- Underpinning research in advanced fuels, in materials and in modelling are UK strengths, and we see evidence for new communities forming to explore nuclear materials for both fission and fusion.
- The UK has a leading international position in magnetic confinement fusion, particularly via the research facilities at Culham Centre for Fusion Energy. JET's (Joint European Torus) restarting D-T (Deuterium-Tritium) operation is critical to the ITER (International Thermonuclear Experimental Reactor) collaboration, and JET should be reviewed in approximately 5 years. MAST-U (Mega Amp Spherical Tokamak Upgrade) will provide a world-leading experimental facility, which should operate for a decade.
- The UK has a strong research community in lasers and plasmas that is contributing to large international programs relevant to inertial confinement fusion, and is appropriately supported through the plasma and lasers research area.
- Though outside the remit of the EPSRC, oversight and advice to government is provided by an overlapping and complex structure, which we would recommend be simplified.

- There are opportunities to exploit developed skills in remote handling and robotics that would be of importance to a larger community.

Process

The Panel gathered information through a variety of routes including: submissions of evidence received through an open survey, meetings with representatives of the key policy, industry, government and advisory groups, meetings with a selected group of leading researchers from the UK fusion and fission communities, data on EPSRC's support, background papers and reports and their own knowledge. Further detail on the review process is available in the annexes to this report.

Glossary

AWE	Atomic Weapons Establishment
AGR	Advanced Gas-Cooled Reactors
BIS	Department for Business, Innovation & Skills
BGS	British Geological Society
BNFL	British Nuclear Fuels Ltd
BWR	Boiling Water Reactor
CCA	Climate Change Act
CCC	Climate Change Committee
CCFE	Culham Centre for Fusion Energy
CDT	(EPSRC) Centre for Doctoral Training
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CEGB	Central Electricity Generating Board
CLF	RAL's Central Laser Facility
CPAC	CCFE Programme Advisory Committee
CoRWM	Committee on Radioactive Waste Management
CSR	Comprehensive Spending Review
DCF	Dalton Cumbria Facility
DECC	Department of Energy & Climate Change
DEMO	DEMOnstration Power Plant
DECC	Department for Energy and Climate Change
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Science Research Council
ERP	Energy Research Partnership
Euratom	European Atomic Energy Community
ETI	Energy Technologies Institute
F4E	Fusion for Energy
FAB	Fusion Advisory Board
FCO	Foreign and Commonwealth Office
GO Science	Government Office of Science
GCSA	Government Chief Scientific Adviser
GIF	Generation IV Forum
GoCo	Government-owned contractor-operated body
HEDP	High Energy Density Physics

HiPER	HIgh Power laser Energy Research Facility
HSE	Health and Safety Executive
ICF	Inertial Confinement Fusion
IEA	International Energy Agency
IAEA	International Atomic Energy Agency
IFE	Inertial Fusion energy
ISIS	The pulsed neutron and muon source at the Rutherford Appleton Laboratory in Oxfordshire. Owned and operated by the STFC.
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
KNOO grant)	Keeping the Nuclear Option Open (An RCUK consortium
LCICG	Low Carbon Innovation Co-ordination Group
LMJ	Laser Megajoule
LWR	Light Water Reactor
MAST	Mega Amp Spherical Tokamak
MAST-U	Mega Amp Spherical Tokamak Upgrade
MFE	Magnetic Fusion Energy
MoD	Ministry of Defence
MOX	Mixed Oxide Fuel (a nuclear fuel type)
NAMRC	Nuclear Advanced Manufacturing Research Centre
NDA	Nuclear Decommissioning Authority
NDE	Non-Destructive Evaluation
NDF	Nuclear Development Forum
NDT	Non-Destructive Testing
NEA	Nuclear Energy Agency
NERC	Natural Environment Research Council
NIA	Nuclear Industries Association
NIC	Nuclear Industry Council
NIF	National Ignition Facility
NIRAB	Nuclear Innovation Research Advisory Board
NIRO	Nuclear Innovation Research Office
NNL	National Nuclear Laboratory
NNUF	National Nuclear User Facility

NRCG	Nuclear Research Co-ordination Group
NRI	Nuclear Research Index
NuSAC	Nuclear Safety Advisory Committee
OECD	Organisation for Economic Co-operation and Development
OND	Office for Nuclear Development
ONR	Office for Nuclear Regulation
PWR	Pressurised Water Reactor
RAL	Rutherford Appleton Laboratory
RCUK	Research Councils UK
RWMD	Radioactive Waste Management Division
SAC	RCUK Energy Programme Scientific Advisory Committee
SME	Small and Medium-Sized Enterprise
SMP	Sellafield MOX plant
SQEP	Suitably qualified and experienced personnel
STEM	Science, Technology, Engineering and Maths
STFC	Science and Technology Facilities Council
THORP	Thermal Oxide Reprocessing Plant
TIC	Technology Innovation Centre
TINA	Technology Innovation Needs Assessment
TRL	Technology Readiness Level
UKAEA	UK Atomic Energy Authority
UKTI	UK Trade & Investment
UKERC	UK Energy Research Centre

Annex 1: Panel Membership

The independent Review Panel consisted of high standing UK and international members:

- Professor Peter Littlewood, Argonne National Laboratory - Chair
- Professor Rajagopala Chidambaram, Principal Scientific Adviser to the Indian Government
- Dr David Clarke, Energy Technologies Institute
- Professor Richard Jones, University of Sheffield
- Professor Richard Jones, DSTL
- Professor Stewart Prager, Princeton Plasma Physics Laboratory
- Professor Takayuki Terai, The University of Tokyo
- Professor Cherry Tweed, Radioactive Waste Management Limited
- Professor Steven Zinkle, University of Tennessee

Annex 2: Objectives

Objectives:

- An independent review of the quality of the current research supported in the UK with a focus on EPSRC's remit but informed by the research supported across the breadth of the Research Councils
- A review of UK research benchmarked against the best international research, resulting in the identification of the UK's unique capabilities, and recommendations for future international engagement
- Identification of progress that has been made as a result of changes within the landscape over the last 10 years e.g. MAST Upgrade, delays to ITER, increased research support for fission
- The consideration of possible future global development scenarios, the UK's role within these, and recommendations for future long-term research strategies for the Research Councils
- A view on the current level of understanding of the science and/or engineering in plasma physics, materials and systems engineering, and the potential opportunities, including for the UK
- Identification of synergies between fission and fusion, and recommendations to enhance joint working
- Review of doctoral training to date and a recommendation of future needs, taking into account the breadth of possible career paths and future sector capability needs
- A recommendation on the future relative proportion of the RCUK Energy Programme's budget to be invested in fission and fusion

Annex 3: Review Criteria

Criteria:

1. **Quality** – Scientific quality of the research and its international standing
2. **People** - The extent to which the current and future capability meets the needs of the sector
3. **National Importance** - The importance of the research to the UK
4. **Impact** - The demonstrable contribution that the research makes to society and the economy

Strategy and Planning – although not an assessment criterion the Panel were invited to provide comments on Strategy and Planning to help guide our future activities in the medium to long term.

1. Quality

Key question: What is the scientific quality of this work and how does it rate internationally?

Sub questions:

a. What is the international standing of the research?
b. Is the research output of this research group highly regarded by the international community?
c. To what extent is the research taking a multidisciplinary approach?
d. Is the research blue skies and long term or taking a short term more incremental approach?
e. Does the research include international collaboration and does this enhance the project?

2. People

Key question: Does the current and future capability meet the needs of the sector?

Sub questions:

a. Are the academics in the project regarded as leading researchers internationally?
b. What involvement have early career researchers had and how has this aided their career development?
c. Was the team able to recruit and retain enough graduates and post-doctoral researchers in this research field or is there a shortage of suitable recruits?
d. Are there sufficient visionary and inspirational research leaders in this field?
e. Do we have sufficient capability to meet our national sovereignty requirements?

3. National Importance

Key question: What is the importance of the research to the UK?

Sub questions:

a. How does the research contribute to current or future UK societal challenges and/or economic success and/or enable future development of key emerging industry(s)?
b. How does the research meet national strategic needs by establishing or maintaining a unique world leading research activity?
c. How does this research complement other UK research already funded in the area, including any relationship to the EPSRC portfolio?
d. How does this research complement other research already funded in the area outside the UK?
e. Does this research contribute to, or help maintain the health of other research areas and if so what are those areas?

4. Impact

Key question: What level of impact has the research had on the UK economy and society?

Sub questions:

a. Is the team ensuring it will achieve the maximum impact from and exploitation of their research?
b. What links does the team have with users of research?
c. Are there are success stories of impact from this project – for example has the research enabled the team to develop any businesses/spin-outs or any societal benefits?
d. Does the project include any public engagement activities or plans?
e. How are we positioned for exploitation of this research both in the UK and internationally?

5. Strategy and Planning – comments to inform EPSRC's future planning

Sub questions:

a. Which countries, including the UK, are internationally leading in this research area?
b. Are there gaps in the UK capability in this research area?
c. Where do the next big challenges lie in this research area? And can the UK be internationally leading in these areas?
d. What are the current and emerging major innovations of benefit to the UK in this research area?

e. Has research in this area been used to address current and emerging technological/societal challenges? If not, what improvements could be implemented to allow this?

Annex 4: Background Information

Call for Evidence

In order to provide a wide evidence base for the Review Panel EPSRC invited submissions of evidence through an on-line survey advertised openly on EPSRC's website. 41 responses were received and these responses and an executive summary were made available to the Panel.

The questions asked in the survey were based on the objectives of the review, and were used to guide the discussions in meetings with different representatives.

The questions that were asked were:

- Within your field of expertise, what is your opinion on the current level of understanding of the science and/or engineering that is relevant to fusion and/or fission?
- What are the potential opportunities, both internationally and for the UK?
- How would you rate the UK's international standing in nuclear fission or nuclear fusion research?
- Who should the UK be working with internationally and why?
- Do you think the UK has the correct balance of funding between bilateral research calls with other countries and participation in major international projects?
- What progress has been made in the UK over the last ten years in nuclear fission and fusion research?
- What do you see the future global research scenarios to be in the fission and fusion sector, and how do you think the UK, and in particular the Research Councils, should be positioning itself with respect to them?
- Does the current UK fusion and fission research activity address the appropriate short, medium and/or long term research requirements of the sector?
- What is your view on the current and necessary relative timescales that fission and fusion research require?
- What synergies do you see between fission and fusion research and how can joint working in these areas be enhanced?
- Are the sectors future capability needs covered by the doctoral training currently provided, and is this training of sufficient quality?
- Are the sectors future capability needs covered by the undergraduate and Masters programmes currently provided, and is this training of sufficient quality?
- Is there sufficient access for UK researchers to world-leading facilities?
- What are your thoughts on the balance of EPSRC funding within the fusion and/or fission research landscape; between fusion and fission research; and between fusion/fission and other energy research areas.

Additional Information

The Panel were provided with additional papers which detailed:

- The funding landscape for nuclear
- EPSRC support (current and past) for research and capacity building
- Advisory bodies

EPSRC's current support for nuclear can be seen by visiting the following pages:

- Fission http://gow.epsrc.ac.uk/NGBOChooseTTS.aspx?Mode=ResearchArea&ItemDesc=Nuclear+Fission
- Fusion http://gow.epsrc.ac.uk/NGBOChooseTTS.aspx?Mode=ResearchArea&ItemDesc=UK+Magnetic+Fusion+Research+Programme
- Plasma and Lasers* http://gow.epsrc.ac.uk/NGBOChooseTTS.aspx?Mode=ResearchArea&ItemDesc=Plasma+and+Lasers

*Not all grants in this research area are of relevance to fusion

Annex 5: Meetings with representatives of the key policy, industry, government and advisory groups

Representatives from the organisations detailed below were invited to meet with the Panel, and give a brief overview (other than the industrial representatives) of their organisation.

Subsequent discussion was structured around the questions from the call for evidence.

Government departments
Department of Business, Innovation and Skills (BIS)
Department of Energy and Climate Change (DECC)

Research Advisory Bodies
Fusion Advisory Board (FAB)
Nuclear Innovation Research Advisory Board (NIRAB)

Non-University Based R&D Organisations and ITER
Atomic Weapons Establishment (AWE)
Culham Centre for Fusion Energy (CCFE)
Dalton Cumbria Facility (DCF)
International Thermonuclear Experimental Reactor (ITER)
Nuclear Decommissioning Authority (NDA)
National Nuclear Laboratory (NNL)
National Nuclear User Facility (NNUF)
Sellafield

Industry
Amec Foster Wheeler
Assystem UK
EDF
First Light Fusion
Tokamak Energy
Westing House

Annex 6: Meetings with a selected group of leading researchers from the UK fusion and fission communities

Grant holders of key CCFE and university-led projects were invited to present a poster for review by the Panel. Members reviewed a subset of the posters using a review template and the assessment criteria.

To allow the Panel to meet representatives of all career stages, each project holder was asked to bring an early career researcher or post-doctoral researcher. Academics representing the Centres for Doctoral Training were asked to bring two student representatives.

Project holders were asked to produce a tailored poster for this session which addressed the review criteria and covered the following points:

- **Quality**: Summary of the research project, progress to date and future plans, bringing out the novelty and international standing
- **People**: The project's contribution to the current and future capability needs of the sector
- **National Importance**: The importance to the UK of the research
- **Impact**: The potential impact of the research and their plans to deliver impact
- **Future Strategy**: The future major research challenges in the area.

In the afternoon a series of discussions between smaller groups of researchers and two sub-groups of the Panel were held:

- Sub group 1
    - 14:00 - 15:00 - Technology - fusion
    - 15:00 - 16:00 - Plasma physics - fusion
    - 16:15 - 17:15 - Materials - fusion and fission
- Sub group 2
    - 14:00 - 15:00 - Decommissioning - fission
    - 15:00 - 16:00 - Future Systems - fission
    - 16:15 - 17:15 - Fuel cycle - fission

Project holders present:

- Tim Abram, The University of Manchester
- Tony Arber, University of Warwick
- Nigel Badnell, University of Strathclyde
- Colin Boxall, Lancaster University
- Ian Chapman, Culham Centre for Fusion Energy
- Sandra Chapman, University of Warwick
- Jerry Chittenden, Imperial College London

- John Collier, STFC Rutherford Appleton Laboratory
- Michael Coppins, Imperial College London
- Kieran Gibson, University of York
- Neil Hyatt, University of Sheffield
- Bill Lee, Imperial College London
- Rebecca Lunn, University of Strathclyde
- Costanza Maggi, Culham Centre for Fusion Energy
- Andy Mount, University of Edinburgh
- Paul Mummery, The University of Manchester
- Martin O'Brien, Culham Centre for Fusion Energy
- Claudio Paoloni, Lancaster University
- Michael Preuss, The University of Manchester
- Steve Roberts, University of Oxford
- Roland Smith, Imperial College London
- Laurence Stamford, The University of Manchester
- Liz Surrey, Culham Centre for Fusion Energy
- Chris Waldon, Culham Centre for Fusion Energy
- Justin Wark, University of Oxford
- Howard Wilson, University of York
- Karl Whittle, University of Sheffield
- Matt Zepf, Queens University Belfast