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An Updated 20-year Vision for the UK Contribution to Fusion as an Energy Source

Research Councils UK
Energy
For a Low Carbon Future

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EXECUTIVE SUMMARY

Nuclear fusion as an energy source has the potential to radically change the world's energy supply providing low-carbon and safe energy for thousands of years.[1]

The UK has been a leader in the development of fusion energy for many years with the highlight being the construction and operation of the world's most successful fusion experiment to date on UK soil, Europe's Joint European Torus (JET). In addition to this, the UK has leading expertise in a number of areas including tokamak science, materials modelling, plasma diagnostics, laser technology and targetry.

Despite many years of development, there are still large technological and physical barriers to be overcome before fusion energy can become a commercial reality. The UK has the opportunity to play a significant role building on years of investment in skills, expertise and infrastructure.

The UK should continue its alignment to the EU Roadmap in Magnetic Fusion Energy (MFE). There is not yet full international agreement on the fusion technology development path but the UK should seek opportunities to align where appropriate to the timelines and preferred approach for any International Fusion Materials Test Facility (IFMIF) or Component Test Facility (CTF).

The world-leading JET facility will remain as a key asset in support of the International Thermonuclear Experimental Reactor (ITER) until at least 2018. JET needs to continue to substantially reduce risk to ITER operations; this may include operation into the next decade.

At the Culham Centre for Fusion Energy (CCFE) the upgraded Mega-Amp Spherical Tokamak (MAST) machine (MAST-U) will provide essential results for future demonstration power plant (DEMO) concepts as well as supporting physics for ITER. Results from MAST-U will influence assessments of the viability and necessity of a CTF in the world fusion programmes and the UK should seek to collaborate with countries pursuing CTF-related activities.

The UK should leverage extensive hands-on experience in fusion science and technology derived from operating and managing JET, and the UK should explore options around various scenarios, including a bid to host the EU Design Centre for a fusion demonstration reactor (DEMO). Hosting the DEMO Design Centre would be a major international activity and would position UK universities and industry to take leading roles in the development of a future fusion-based power industry.

In the event of ignition at the National Ignition Facility (NIF), an international consortium should be launched in Inertial Fusion Energy (IFE) and the UK should play a leading role in this consortium. Possible options for such a consortium should be explored in advance of ignition in order for the UK to maintain its leadership. The UK should contribute to efforts to understand why ignition at NIF has been delayed.

The UK should maintain its world leadership role in Inertial Confinement Fusion (ICF)/IFE-related science and technology by implementing the planned 20PW Vulcan Upgrade at the Rutherford Appleton Laboratory. In addition, the UK should appropriately integrate AWE capabilities into the IFE effort.

The UK Government should establish a single organisation responsible for development of an integrated IFE strategy that considers both direct-drive and indirect-drive e.g. HiPER or equivalent demonstration facilities. This organisation should draw together national labs and universities in the execution of this function.

[1] http://fusionforenergy.europa.eu/understandingfusion/

The European Fusion Roadmap has missions to develop the neutron resistant materials necessary for fusion power by utilising an Early Neutron Source (ENS) through collaboration with Japan. The location and detailed scope of this are yet to be determined. A source hosted by the UK is one possible option and, if favoured by EUROFusion/F4E, then national funds should be sought to support a bid.

The UK's continued support for materials science and development in the UK is key to advancing nuclear fission plans, as well as to remove roadblocks in fusion on the way to commercially viable power plants.

Remote handling should be pursued in the UK as a key technology for continued strong engineering participation in the ITER construction and enhancement phases, as well as to engage in DEMO design and construction activities.

National laboratories should continue to partner with universities in science and technology activities to maintain the necessary influx of knowledge and talent that the UK fusion programme requires.

For industry involvement in fusion energy changes in the Fusion for Energy organisation (F4E) have led to a more balanced allocation of risk in contracts and there is now a much more favourable environment for UK contracting to ITER. In preparation for the longer term DEMO development, it is essential that UK industry and CCFE form effective partnerships to allow an early and strong industrial input as foreseen in the EU Roadmap.

If the UK takes the decision to participate in the developmental phases of IFE (HiPER or equivalent demonstration facilities), a skills base and manufacturing capability will need to be built up for the UK to be in a position to benefit. To facilitate this industry will need to be engaged at an early stage. This should be supported by a funding environment that substantially reduces the risk of early-stage participation by UK industry.

1 INTRODUCTION

Nuclear Energy is a mature, reliable low carbon technology with a secure and abundant fuel source and is an essential contributor to the energy mix.[2] UK energy scenarios highlight a potential increase of peak energy demand from 80 to 300 GWe by 2050. As such there is a potential increase in UK Nuclear Energy requirements from 16 to 75 GWe over this timeframe and various scenarios are currently being evaluated. Fission and fusion will play an important role in achieving this.

This Vision outlines where the UK should contribute to the worldwide development of fusion energy over the next 20 years. Updated from the original Vision published in 2010[3], it defines where the UK is helping to secure the world's long-term energy supply through the development of fusion energy and how the UK aims to benefit from the opportunities arising from fusion-related research in the UK and elsewhere.

The Vision has been formed by a working group (**Annex A**) made up largely from a subset of the Fusion Advisory Board[4], and inputs have been gathered from a variety of national and international stakeholders (**Annex B**) to inform this process. This document also informs the Research Councils UK Energy Programme 10-year Fusion for Energy Strategy.

[2] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/168048/bis-13-627-nuclear-industrial-strategy-the-uks-nuclear-future.pdf

[3] https://www.epsrc.ac.uk/newsevents/pubs/a-20-year-vision-for-the-uk-contribution-to-fusion-as-an-energy-source/

[4] http://www.rcuk.ac.uk/research/xrcprogrammes/energy/rcukfab/

2 CURRENT INTERNATIONAL PATHWAY TO FUSION AS AN ENERGY SOURCE

There are two main routes to fusion energy, magnetic fusion energy (MFE) and inertial confinement fusion (ICF) as described in **Annex D**.

The international strategy for MFE is centred on the €15Bn International Thermonuclear Experimental Reactor (ITER)[5] experiment currently being built in Cadarache, France. ITER will be the first device to release reactor-relevant fusion power (~ 500MW for hundreds of seconds) and it will be the first experiment to study the 'burning plasma' regime, wherein the heating of the plasma fuels is dominated by the energy released from the fusion reactions themselves; this will represent a crucial test of the feasibility of magnetic fusion as a massive source of energy. The ITER Management Assessment report recommends urgent changes in which the UK can play an important role.

Of the seven partner organisations the EU is the biggest with 45% of the overall contribution. Alongside the EU's commitment to ITER there is concurrent support to achieve the objectives of the European Fusion Roadmap, released in 2012.[6] This defines a number of missions from experiments that need to be done now in order to support ITER to the design of a demonstration reactor (DEMO), able to provide electricity to the grid by 2050.

A key element in this Roadmap is the UK-operated JET facility, currently the largest magnetic fusion device in the world and one of only two devices in the world to have achieved significant fusion power (in 1997 JET produced 16MW of fusion power from a total input of 24MW). JET will play an important role during the next 5-10 years in support of ITER construction choices and preparation of its operation.

Other proposed large facilities thought to be necessary for achieving fusion energy include an International Fusion Materials Irradiation Facility (IFMIF) and a more advanced Component Test Facility (CTF – possibly in collaboration with the USA and China). The latest European plans for DEMO do not require these although they would require a 14MeV Early Neutron Source (ENS).

ICF activities are on-going in a number of nations, including the UK, France and other EU countries, the USA, Japan, Russia and China. Many of these activities are focused around large laser facilities including the European High Power laser Energy Research facility (HiPER) Project, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in the USA, the International Laboratory Inertial Fusion Test (i-LIFT) project in Japan and other efforts in South Korea and elsewhere. The Extreme Light Infrastructure (ELI) Project and other worldwide activities in the rapidly evolving field of high intensity laser research also contribute significantly to advancing the inertial fusion scientific and technology base.

An international strategy for ICF is yet to be developed although ICF research continues to make strong progress around the world, with significant results from NIF and the construction of similar large laser facilities planned or underway. NIF has recently obtained record ICF yields, including the first demonstration of total fusion yield exceeding the amount of energy deposited into the deuterium-tritium fuel and central 'hotspot' during the implosion process.[1]

The UK continues to play a strong leadership role in ICF via the HiPER project and is looking to develop an inertial fusion energy (IFE) strategy through the network led by Imperial College.[7] Through the work conducted in Europe within the HiPER Preparatory Phase under STFC leadership, and efforts at the Lawrence Livermore National Laboratory and elsewhere, a coherent international plan for the exploitation of NIF ignition from an energy perspective is

[5] http://www.iter.org/
[6] https://www.euro-fusion.org/eurofusion/the-road-to-fusion-electricity/
[7] http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/L000822/1

emerging.

2.1 Current UK Contribution to Magnetic Fusion Energy

The 2012 European Roadmap towards fusion electricity in 2050 describes the path from JET to ITER through to DEMO and then commercialisation (**Figure 1**). Before DEMO can be built an ENS is required to test the reactor materials. There are several concepts for this including the CCFE-proposed Facility for Fusion Neutron Irradiation Research (FAFNIR[8]) and the option, currently favoured by F4E, of an ENS based on components that will be available following conclusion of the IFMIF/EVEDA project in Japan.

In addition to JET, CCFE runs the Mega Amp Spherical Tokamak (MAST). MAST is currently undergoing an upgrade (MAST-U). MAST-U will play an important role in preparation for DEMO through development of advanced divertors including the so-called 'super-X' divertor concept. This could offer a solution to the excessive power loads taking place in standard divertor geometries and solve one of the critical challenges for fusion energy.

MAST-U is also amongst the leading candidates to test the feasibility and inform the design of a CTF, alongside its sister experiment the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory in the USA. Important ITER research needs will also be strongly supported by MAST-U research tackling a number of highly relevant physics problems.

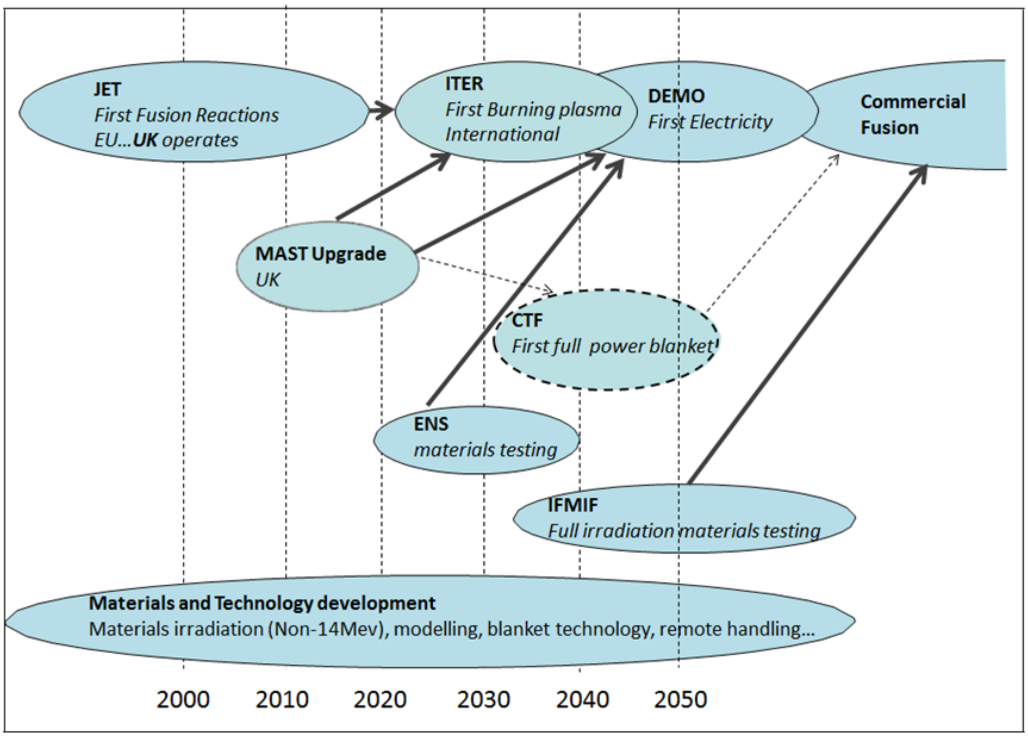

Figure 1 Indicative EU/International pathway to magnetic fusion at end of 2014

Lastly, MAST-U will provide university and CCFE researchers with an important UK training-ground for performing tokamak experiments, developing diagnostic methods and analysis techniques, and model validation, in preparation for participation in team-based research on ITER, especially if JET is no longer operational in the early 2020s.

Vision: *The UK should continue its alignment to the EU Roadmap in MFE as proposed in Figure 1. There is not yet full international agreement on the fusion technology development path but the UK should seek opportunities to align where appropriate to the timelines and*

8 http://www.ccfe.ac.uk/assets/Documents/CCFE-PR(13)39.pdf

preferred approach for any IFMIF or CTF facility. The UK should explore options around various scenarios, including a bid to host the EU Design Centre for a fusion demonstration reactor (DEMO). Hosting the DEMO Design Centre would be a major international activity and would position UK universities and industry to take leading roles in the development of a future fusion-based power industry.

2.2 Current UK Contribution to Inertial Confinement Fusion

The next critical step in the path to IFE is the achievement of fusion ignition and gain. Ignition is a central goal of NIF completed in March 2009. While ignition hasn't yet been achieved, NIF recently recorded record fusion yields. The UK contribution could be very valuable in understanding why ignition has been delayed. In addition over 100 companies have been involved in 'preparatory phase' power plant design activities.

The UK contributes to ICF in a number of areas including laser technology, targetry and plasma diagnostics. The UK's interest in laser technology extends beyond fusion with significant opportunities (some realised already) commercially such as the pan-European Extreme Light Infrastructure (ELI) project.

While the IFE presence in the UK is much more modest compared to the MFE effort, a national network in IFE has been supported which aims to deliver a UK roadmap, and several collaborations between the USA and UK have been funded by EPSRC.[9]

The UK has shown strong leadership by proposing and coordinating the HiPER project where activity is focused on direct-drive IFE. The UK also has strong indirect-drive related capabilities at the Atomic Weapons Establishment (AWE), Aldermaston, and elsewhere. The UK is developing an integrated IFE science and technology programme via HiPER, an on-going EPSRC networking activity and other efforts, and will consider both direct-drive and indirect-drive in this planning effort.

Vision: *In the event of ignition at NIF, an international consortium should be launched in IFE and the UK should play a leading role in this consortium. Possible options for such a consortium should be explored in advance of ignition in order for the UK to maintain its leadership. The UK should contribute to efforts to understand why ignition at NIF has been delayed.*

3 OPPORTUNITIES AND BARRIERS FOR THE UK TO PLAY A LEADING ROLE IN THE DEVELOPMENT OF FUSION AS AN ENERGY SOURCE

3.1 Opportunities and Barriers for the UK in MFE

The UK has played an internationally leading role in the development of MFE for over 50 years. This has included the operation and exploitation of JET in a European context and the advancement of the spherical tokamak approach from the Small Tight Aspect Ratio Tokamak (START) in the 1990s to MAST-U. In the future, the experience in operating JET under deuterium-tritium (D-T) conditions will be essential to the success of ITER. Thus the continuation of JET until 2018 is an essential step in maintaining the bridge towards ITER, and the UK is a major participant in the exploitation.[10]

In parallel, the operation and further exploitation of MAST together with wider participation in international tokamak science research, will maintain UK strengths in plasma physics and in exploring frontiers of device operation that may provide essential knowledge for the design

[9] http://gow.epsrc.ac.uk/NGBOViewPanelROL.aspx?PanelId=1-192FNH&RankingListId=1-196CE9

[10] The UK involvement in the exploitation is funded jointly by EPSRC and EUROfusion, outside the new JET Operation Contract

and operation of DEMO. In addition, the last ten years saw the foundation of a science-based materials programme that is geared towards atomistic and micro-scale understanding of radiation damage in fusion, but also in the fission environment. It is against this backdrop that the opportunities and barriers are considered.

3.1.1 Exploitation of JET and ITER

JET is currently the largest and most powerful magnetic fusion device in the world and the only one that is capable of using D-T fuel. It will continue to contribute to tritium-related issues that will be very relevant for the future nuclear licensing of ITER. The value of JET for validating ITER physics issues has been outstanding and will remain so in the near term. In particular, the results from operation with the 'ITER-like' wall (2011 onwards) have contributed significantly to the ITER decision to go directly to a tungsten divertor, reducing risk as well as saving time and budget.

JET activity in support of ITER construction and operation was strongly supported by an independent expert review panel for the European Commission in 2011. Despite budget pressure from ITER construction costs, funds have been secured for the operation of JET until 2018 and a five-year contract has been established between EURATOM and CCFE for JET operation. The next JET tritium campaign is planned for 2017 and should set new fusion power records. JET needs to continue to substantially reduce risk to ITER operations; this may include operation into the next decade.

Vision: *The world-leading JET facility will remain as a key asset in support of ITER until at least 2018. Despite general budget pressure, operation for the coming five years has been secured. JET needs to continue to substantially reduce risk to ITER operations; this may include operation into the next decade.*

3.1.2 MAST Upgrade

MAST-U will be the first machine in the world capable of testing the super-X divertor. The divertor is a critical part of the exhaust system for any tokamak. Dealing with the divertor heat load is specifically crucial in spherical tokamaks but affects **all** tokamaks including DEMO. The advanced divertors explored on MAST-U (including the super-X) may provide a solution. The super-X divertor studies enhance the potential of spherical tokamaks to contribute also to the main line in critical development areas.

The proposed CTF is potentially an important part of the materials and component testing effort. One of the concepts offered for a CTF is based on the spherical tokamak, but the optimum design with regard to aspect ratio, operational scenario and divertor configuration has still to be found. The optimal configuration will be explored over the next few years and the results from MAST-U (and NSTX Upgrade in the USA) could be critical to this discussion. If the spherical tokamak proves to be the best approach, then MAST-U would be a major contribution to expediting this strategy.

Vision: *The upgraded MAST machine will provide essential results for future DEMO concepts as well as supporting physics for ITER. There is not yet consensus on the need for a CTF in the international pathway but results from MAST-U will have significant influence on assessments of the viability and necessity of a CTF in the world fusion programmes. UK collaboration with other countries pursuing CTF programmes might be an attractive means of participation in CTF-related activities.*

3.1.3 Development of an Early Neutron Source for Materials Testing

The realisation of fusion power requires enhanced effort on materials, first-wall, blanket and other technologies. Due to resource and other constraints, effort in this area worldwide over the past several decades has lagged compared to the optimisation of high-performance plasmas. With the decision to realise ITER, this shortfall in effort must be addressed to take full advantage of ITER and prepare for DEMO.

IFMIF is an important part of this effort but with the reduction in materials requirements for DEMO and the long timescale of IFMIF construction, the EU Roadmap recognises the need for an ENS. Several concepts exist for this including the CCFE-proposed FAFNIR, which could be built within about ten years, possibly in the UK, to complement fission options, including the Jules Horowitz reactor (on-line in France in ~ 2019). Under EUROFusion and Fusion for Energy (F4E) a review of 14MeV neutron sources for radiation damage measurements has been conducted to identify the main facility the EU will use.

Vision: *The European Fusion Roadmap has missions to develop neutron resistant materials for the first-wall/blanket and divertor utilising an ENS possibly through collaboration with Japan. Several concepts for this ENS exist, including the CCFE-proposed FAFNIR. While there is consensus around the need for such a source, the location and detailed scope is yet to be determined. A source hosted by the UK is one possible option and, if favoured by EUROFusion/F4E, then national funds should be sought to support a bid.*

3.2 Opportunities and Barriers for the UK in ICF

The UK has a long and distinguished record of scientific achievement in areas such as astrophysics, material sciences, hydrodynamics, interaction of radiation with matter and other topics in high energy density (HED) science central to the physics of ICF targets. With the construction and operation of the VULCAN laser, and upgrades, at RAL, together with the HELEN and now ORION lasers at AWE, the UK is also a leader in the construction and operation of high-energy, high-power inertial fusion facilities. The UK is thus well-positioned to take advantage of the emerging opportunities in IFE.

3.2.1 Enhancement of the UK Scientific Base in ICF/IFE-related Science via Experiments at NIF, LMJ, and other Facilities

The UK is well positioned to enhance its role as scientific leader via execution of experiments on NIF, Laser Mégajoule (LMJ) in France and other facilities as these capabilities become available. EPSRC has recognised this opportunity by funding an individual investigator programme focussed on ignition-related science at NIF. This successful effort is increasing the visibility of UK scientists in the worldwide ignition effort and helping to build and sustain the base HED science programme in the UK. The UK Centre for Inertial Fusion Science (CIFS) provides the opportunity for more effective integration of UK academic, industrial, and private sector capabilities in pursuit of ICF/IFE. The CIFS also provides a point of contact for international collaborations.

The expert group notes the role of the RAL Central Laser Facility (CLF) as a leader in many areas of HED science and technology directly relevant to ICF/IFE. Numerous leaders in ICF/IFE worldwide have been trained at CLF. Long-standing plans to implement the VULCAN 20PW upgrade at CLF would be of great benefit to this effort. CLF's continuation as world leader in HED science is important to maintaining the ICF-related UK scientific base and realising IFE opportunities. In particular, a modernised CLF will serve as an essential precursor/staging facility for researchers involved in experiments at the LMJ and NIF megajoule-scale facilities.

The expert group also notes the very significant expertise in HED science at AWE and recommends the Government examine means to apply this expertise to the UK IFE effort.

Vision: *The UK should maintain its world leadership role in ICF/IFE-related science and technology. In addition, the UK should appropriately integrate AWE capabilities into the IFE effort.*

3.2.2 Leading Collaborations in the Emerging Area of ICF/IFE

The UK is well positioned to serve as a world leader in IFE via the presence of a strong scientific base in HED science, experience operating large laser facilities, and the presence of significant laser, target fabrication, optics, and other IFE related technology expertise in academia, laboratories, and the private sector. IFE-related technology activities of particular note include the HiLASE project in the Czech Republic, developing Diode Pumped Optical Laser for Experiments (DiPOLE) technology, participation in the ELI Project, optical manufacturing work at Cranfield and in the private sector, and tritium-related work at BNFL, NNL, and AWE.

The HiPER project is the major example of the UK realising this leadership opportunity. The HiPER Preparatory Phase has been completed and the next phase, 'Ignition Physics, Technology Development and Risk Reduction', commenced in April 2013. The recommended near-term strategy is to focus the HiPER effort on the development of a detailed UK and international plan for IFE, contingent upon the successful achievement of ignition at NIF.

If a global collaboration cannot be formed, then the strength of the international competition is a barrier to the progression of the HiPER project as it currently stands. In the event NIF ignition is not achieved, inertial fusion will revert to its historical role within the research councils' broader physical sciences portfolio. This would include studies of advanced fusion options such as 'fast ignition', an alternative to the 'hot-spot' ignition being pursued at NIF. The UK could be an effective leader of international efforts in this area as well.

Vision: *Historically, the UK has neither had a clearly defined programme in IFE nor a unified inertial fusion strategy. Support of the EPSRC IFE Network and leadership of the HiPER project presents an opportunity to develop such a strategy. The UK Government should develop an integrated IFE strategy that considers both direct-drive and indirect-drive e.g. HiPER or equivalent demonstration facilities. The UK Government should also establish a single organisation responsible for development of this integrated strategy. This organisation should draw together national labs and universities in the execution of this function.*

3.3 Cross Cutting Science and Engineering

Theory, modelling and materials science have been subjects where strong links with UK universities have been established, significantly strengthening these fields of activity. This forms a sustainable source for the influx of knowledge and young scientists into the UK fusion programmes.

A further step forward has been the establishment of a National Nuclear User Facility (NNUF) for the investigation of nuclear fission and fusion materials, both under basic science aspects and under realistic operation conditions. This puts the materials research field into a position to strongly support the development of a knowledge base to revamp the UK nuclear fission reactor fleet and to draw on independent knowledge on materials behaviour when the operational life of UK fission reactors may be extended. For DEMO and future fusion reactors, the UK will strongly contribute to the international knowledge base on the behaviour of materials under severe neutron irradiation and thermal loads. This is internationally needed to develop new and enhanced materials as a prerequisite towards commercially viable fusion power.

Engineering strengths at CCFE, especially, cover all aspects of remote handling as gained from developing and using remote handling equipment at JET. In the future, this will provide excellent opportunities for the UK to lead activities for ITER, both during construction and enhancement phases over the coming decades. This knowledge and technical capabilities may then also be deployed for the development and construction of DEMO.

There are common elements in theory, modelling and materials development, for MCF that are also applicable to ICF. There is also the possibility of regulatory simplicity as the first-wall of the fusion chamber is separated from the containment wall, enabling existing, radiologically qualified materials to be used for the IFE containment.

In IFE, there is currently a lack of sufficiently trained personnel for the UK to develop the IFEspecific materials, engineering and technology required to make IFE a reality. An important part of any global collaboration would be to understand exactly what the needs of a next-step facility such as HiPER would be and how they can be addressed.

Vision: *National laboratories should continue to partner with universities in science activities to maintain the necessary influx of knowledge and talent into the UK fusion programme.*

The UK will continue to support materials science and development in the UK as these are key to advancing the nuclear fission plans, as well as to remove roadblocks in fusion on the way to commercially viable power plants.

Remote handling should be pursued as a key technology for continued strong engineering participation through all ITER construction and enhancement phases, as well as to engage in DEMO design and construction activities.

3.4 Skills

3.4.1 MFE

In recent years, there has been significant strengthening of the relationship between CCFE and the UK university base which is educating the next generation of fusion scientists and engineers. In order to provide the skills required to progress the UK contribution to fusion energy, these investments need to be sustained. Currently, CCFE has a PhD student cohort of over 40 students (for which they provide some funding) spread between three areas: plasma physics (19); materials (10); and technology (13); reflecting increased emphasis on materials and technology. These students come from 16 different universities, with half being based at CCFE and the rest visiting for prolonged periods. There are also students within the broader EPSRC physical sciences portfolio working in areas related to fusion but not receiving funds from CCFE.

As JET operator, CCFE also has unrivalled hands-on experience of fusion technology - particularly with tritium, remote handling, and project management and quality controls to ensure high reliability operation and compliance with a nuclear safety. This experience is an asset for the world fusion programme and will be important for the exploitation of ITER. Through the development of the spherical tokamak concept, CCFE also has expertise in designing and building fusion facilities as demonstrated by the construction of MAST-U, and also has expertise in the development and/or implementation of advanced fusion diagnostics. Such capabilities place the UK in a strong position to propose to lead, or make a major contribution to, an EU DEMO design centre.

3.4.2 ICF

The UK has successfully constructed and operated the VULCAN and HELEN lasers at RAL and AWE respectively, and has delivered the ORION laser at AWE. The ORION system is now one of the premier high-power, high-energy lasers in the world and is open to both the national security and academic research communities (the latter at 15% time). More recently, the UK has become a partner in the ELI Project, a major laser construction effort which will boost UK capability in diode-pumped laser systems.

UK experience with VULCAN and ORION and associated diagnostic systems provides a sound basis for UK leadership and involvement in inertial fusion. In addition, the research programmes at RAL and UK universities have produced numerous high-quality PhD graduates who have gone on to assume leadership roles in inertial fusion efforts around the world. The joint AWE/Imperial College Centre for Inertial Fusion Science, formed in 2009, represents a significant new source of talent for the ICF/IFE effort, for both direct-drive and indirect-drive.

Capability in both IFE and MFE has been enhanced by the EPSRC Centre for Doctoral Training in the Science and Technology of Fusion Energy, hosted by the University of York.

4 INDUSTRIAL ENGAGEMENT WITH FUSION ENERGY

The benefits to UK industry from attempts to realise fusion energy have so far come from contracts for large experiments. The advancement of ITER construction since 2010 has led to increased opportunities for UK companies, with the share of contracts for the UK being above average when compared to other EU countries, with nearly €400 million of ITER contracts won.

Similarly, construction of NIF in the USA has led to c. £50 million of contracts for the optics industry.

4.1 Industrial Involvement in Magnetic Fusion Energy

The balance of future contracts on ITER will be concentrated on the remaining project and construction management and system integration activities at the Cadarache site, with fewer large-scale supply contracts, although the ITER market will continue to provide opportunities in areas such as systems and plant maintenance and replacement, waste management and support to future operation over many years.

More generally, the EFDA Roadmap explicitly identifies the required transition for industrial involvement from providers of high-tech components to drivers of fusion development. It is acknowledged that industry must be able to take full responsibility for the commercial fusion power plant after successful operation of DEMO. The progression to the next stage, i.e. DEMO design and eventual construction, will afford important opportunities for businesses, in particular the traditional nuclear systems engineering companies, who will need to be involved from the very start in the design effort.

Vision: *The changes in F4E have led to a more balanced allocation of risk in contracts and there is now a much more favourable environment for UK contracting to ITER. In preparation for the longer term DEMO development, it is essential that UK industry and CCFE form effective partnerships to allow an early and strong industrial input as foreseen in the EU Roadmap.*

4.2 Industrial Involvement in Inertial Fusion Energy

Supported by the historically strong research base and established expertise in laser design and construction, notably at CLF (DiPOLE), AWE (ORION), the ELI Project, and through leadership of HiPER, the UK is well-placed to benefit from IFE.

Despite this favourable positioning, IFE presents UK industry with significant challenges. The high level of technical and commercial risk, combined with long timescales and the lack of an ignition-scale IFE facility in the UK make it difficult for UK industry to engage with, and benefit from, IFE. Similarly, the lack of an agreed roadmap, national coordinating body or focal point for industry and academia (as exists in France with LMJ Route des Lasers, and in the US with NIF and Silicon Valley) present further barriers for UK industry.

Vision: *If the UK takes the decision to participate in the developmental phases of IFE (HiPER or equivalent demonstration facilities), a skills base and manufacturing capability will need to be built up for the UK to be in a position to benefit. To facilitate this industry will need to be engaged at an early stage due to the highly specialised nature of the products and capabilities required by IFE. This should be supported by a funding environment that substantially reduces the risk of early-stage participation by UK industry.*

5 ADVANTAGES TO THE UK OF BEING INVOLVED IN THE DEVELOPMENT OF FUSION ENERGY AND THE RISKS OF NOT BEING INVOLVED

The potential advantages to the UK of being involved in the development of nuclear fusion over the next ca. 20 years are:

- Opportunities for businesses to be involved in designing, building and licensing reactors and benefits from wider supply chain opportunities
- Continued financial leverage from the EU, with opportunities to expand such financial support ,e.g., from other international partners
- Opportunities for considerable inward investment from the EU and elsewhere (e.g. JET, ITER and DEMO Design Phase)
- Training of highly skilled people contributing to the economic success of the UK in a number of areas, e.g., nuclear fission, advanced lasers/optics, materials, etc.
- Opportunity for the UK to lead international coordination in IFE.

The major risks and disadvantages to the UK of not being involved in the development of nuclear fusion over the next ca. 20 years are:

- Loss of scientific leadership and credibility and damage to the UK’s reputation
- Loss of skills, expertise and capability in the UK – this will lead to reduced benefits to UK business arising from UK supporting research (e.g. ‘up-skilling’)
- Loss of exploitation opportunities arising from ITER even though the UK would still be contributing to EURATOM
- Potential damage to US-UK defence links
- Potential delay in achieving fusion energy or loss of confidence in fusion (MCF and ICF) internationally if UK pulls out
- The UK will be left behind once NIF ignition occurs.

Annex A: Expert Group Membership and Terms of Reference

Expert Group Membership:

Prof Harald Bolt	Forschungzentrum Jülich, Germany
Alain Chevalier	Assystem UK Limited
Gareth Jones	Gooch and Housego
Dr Chris Keane	Lawrence Livermore National Laboratory, USA
Dr Jon Menard	Princeton Plasma Physics Laboratory, USA
Dr Joaquin Sánchez	CIEMAT, Spain
Philip Sharman	Independent (Chair)

Terms of Reference:

The Expert Group was invited to:

1. To provide an update of the 2009 vision document to include recent developments including delays in schedule and changes to the ITER programme and progress in the US towards ignition at the National Ignition Facility.

2. Within the context of the long-term view of the UK contribution to fusion and the European (EFDA) Roadmap to Fusion Energy, to produce a document advising on the pathway for UK fusion in the next 10 years and set out what actions need to be taken to achieve this, including considering the long-term need for experienced and skilled people.

3. To outline the strategic priorities for fusion activity in the UK, including a number of funding scenarios should the funding landscape change.

4. To advise on the steps needed to secure business benefit for the UK including benefits to national and multi-national companies.

Annex B: Evidence Base Consulted

Document	Author/Origin
A HIGH LEVEL EXPERT GROUP on the Assessment of the Projects on the ESFRI Roadmap	European Commission
Workplan 2014-2018 EU Roadmap	EFDA
ESFRI Energy Thematic Working Group Report, 2010	ESFRI
A Roadmap to the Realisation of Fusion Energy, 2012	EFDA
An Assessment of the Prospects for Inertial Fusion Energy, 2013	National Academy of Sciences
Shock Ignition Roadmap for HiPER Final Report, 2013	HiPER Project team
Laser Energy for Europe Outline Business Case 2012	HiPER Project team
A 2013-2020 Roadmap Towards Inertial Fusion Energy	EURATOM IFE KiT activities
ITER Progress Report, 2013	F4E
Technology and Industry Advisory Committee Final Report, 2012	RCUK FAB TIAC
Fusion for Energy Strategy, 2013	CCFE
20-year Vision for the UK Contribution to Fusion as an Energy Source, 2009	RCUK
ITER and UK involvement - Presentation	CCFE

Stakeholders consulted:

- Culham Centre for Fusion Energy
- Rutherford Appleton Laboratory
- UK Universities
- The UK Inertial Fusion Energy Network
- AWE
- RCUK Energy Programme Scientific Advisory Committee
- Physical Sciences Strategic Advisory Team
- US Department of Energy
- The Fusion Industry Innovation Forum
- The Energy Research Partnership
- Euratom
- ITER
- EFDA
- International Fusion Associations
- RCUK Fusion Advisory Board

Annex C: Consultation Questionnaire

Q1. What do you see as the opportunities for UK research to play a leading role in magnetic fusion energy over the next 20 years?

Q2. What do you see as the barriers to UK research playing a leading role in magnetic fusion energy over the next 20 years?

Q3. What do you see as the opportunities for UK businesses in magnetic fusion energy over the next 20 years? Specifically, what are the ITER opportunities experienced to date and anticipated over the next 20 years?

Q4. What do you see as the barriers for UK businesses in magnetic fusion energy over the next 20 years? Specifically, what are the ITER barriers experienced to date and anticipated over the next 20 years?

Q5. What do you see as the risks to the UK of not being involved in the development of magnetic fusion energy over the next 20 years?

Q6. What do you see as the opportunities for UK research to play a leading role in inertial fusion energy over the next 20 years?

Q7. What do you see as the barriers for UK research playing a leading role in inertial fusion energy over the next 20 years?

Q8. What do you see as the opportunities for UK businesses in inertial confinement fusion over the next 20 years?

Q9. What do you see as the barriers for UK businesses in inertial fusion energy over the next 20 years?

Q10. What do you see as the risks to the UK of not being involved in the development of inertial fusion energy over the next 20 years?

Q11. What do you see as the benefits to the UK of achieving fusion as a future source of energy supply?

Q12. What should be the UK's fusion for energy priorities over the next 20 years?

Q13. In the context of the terms of reference for the review do you have any further comments? In particular, please comment on any major developments since the 2009 review that could impact the UK fusion program.

Annex D: An Introduction to Fusion

What is fusion?[4]

Fusion is the process that heats the sun and all other stars. In the sun hydrogen is fused to helium at a temperature of about 15 million °C, releasing an enormous amount of energy that escapes as light.

Fusion occurs when light atomic nuclei overcome the repellent electrical forces and collide together releasing energy in the form of neutrons. This only happens if they collide with a very high speed, which means that the combination of temperature and pressure of the interacting species must be very high. At these very high temperatures, the electrons are separated from their nuclei and together they form a gas of charged particles in which the electrons and nuclei move independently. This state is called a *plasma.* To achieve high enough fusion reaction rates to make fusion useful as an energy source, the fuel (two types of hydrogen – *deuterium* and *tritium* whose nuclei can fuse to form a helium nucleus and a neutron providing a lot of energy) must be heated to temperatures over 100 million °C.

No single material can withstand such temperatures. Therefore, the plasma must be kept away from the walls of the plasma vessel. Otherwise, the plasma would cool down due to impurity radiation, and fusion would stop. For fusion to work as an energy source the plasma must be *confined.*

Magnetic Confinement Fusion[5]

In magnetic confinement strong magnetic fields are used to confine the plasma and avoid contact with the vessel walls. A plasma of light atomic nuclei is heated and confined in a 'doughnut' shaped bottle known as a tokamak, where it is controlled with strong magnetic fields. In a magnetic fusion device, the maximum fusion power is achieved using deuterium and tritium. These fuse releasing 17.6MeV (megaelectron volts) of energy per reaction (1 gram of fusion fuel contains the energy of 10 tonnes of coal). In a commercial fusion plant the neutrons, which carry 80% of the reaction´s power, will be slowed down by a blanket surrounding the machine, and the heat this provides, together with the remaining 20% carried by charged alpha particles and collected at the machine inner wall, will be converted into steam to drive turbines and put power on to the grid.

In the UK this work is led by the Culham Centre for Fusion Energy (CCFE) and is funded by EPSRC and EURATOM.

Inertial Confinement Fusion[6]

The inertial confinement fusion (ICF) approach, examined by the HiPER pan-European conceptual studies and other teams, involves compressing a mm-sized pellet of deuterium-tritium fuel with lasers, or radiation, to high density and high temperature for a for a few billionths of a second. Under the correct conditions, alpha-particles from initial fusion reactions in the hot central compressed core will be deposited into colder deuterium-tritium fuel surrounding the hot centre. This self-heating or 'alpha-heating' process leads to additional fusion reactions. ICF 'ignition' occurs when the total fusion energy output exceeds the input laser energy. The energy from the neutrons and the alpha particles will be collected and converted into electricity in a in a similar way as in MCF reactors (see above).

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[4] For more information and a general overview see http://www.efda.org/

[5] For more information see http://www.ccfe.ac.uk/

[6] For more information see http://www.hiper-laser.org/index.asp

Annex E: Glossary

AWE	**Atomic Weapons Establishment**
CCFE	**Culham Centre for Fusion Energy**
CDT	**(EPSRC) Centre for Doctoral Training**
CLF	**RAL's Central Laser Facility**
CPAC	**CCFE Programme Advisory Committee**
CTF	**Component Test Facility**
DEMO	**Demonstration Power Plant**
DiPOLE	**diode pumped optical laser**
EFDA	**European Fusion Development Agreement**
ELI	**Extreme Light Infrastructure**
ENS	**Early Neutron Source for materials irradiation**
EPSRC	**Engineering and Physical Sciences Research Council**
EU	**European Union**
EUROfusion	**The consortium of EU fusion institutes that is expected to be awarded an EU Horizon 2020 grant**
F4E	**Fusion for Energy**
FAB	**Fusion Advisory Board**
FAFNIR	**Facility for Fusion Neutron Irradiation Research**
HEDP	**high energy density physics**
HiPER	**HIgh Power laser Energy Research facility**
ICF	**inertial confinement fusion**
IFE	**inertial fusion energy**
IFMIF	**International Fusion Materials Irradiation Facility**
IEA	**International Energy Agency**
ITER	**International Thermonuclear Experimental Reactor**
JET	**Joint European Torus**
LMJ	**Laser Mégajoule**
MAST	**Mega Amp Spherical Tokamak**
MAST-U	**Mega Amp Spherical Tokamak Upgrade**
MFE	**magnetic fusion energy**
MOD	**Ministry of Defence**
NIF	**National Ignition Facility**
NIRAB	**Nuclear Innovation Research Advisory Board**
NNL	**National Nuclear Laboratory**
NNUF	**National Nuclear User Facility**
RAL	**Rutherford Appleton Laboratory**
RCUK	**Research Councils UK**
ST	**spherical tokamak**
STFC	**Science and Technology Facilities Council**
TIAC	**FAB's Technology and Industry Advisory Committee**
UKTI	**UK Trade and Investment**