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

February 2010

Research Councils UK Energy Programme

www.rcuk.ac.uk/energy

Executive Summary

The science and engineering research challenges ahead to realise fusion as a commercial energy source are major and the timescales are long and uncertain. Fusion is likely to contribute to energy systems after 2050. The potential of fusion energy to contribute as a major component of the future global energy system is sufficiently large that it should be pursued in the UK; this is an area of international excellence in terms of research and skilled people in the UK which is contributing to a global challenge. It needs continued funding for the long term, even when difficult financial choices are being made. A high-level schematic of the possible UK programme over the next 20 years is given below.

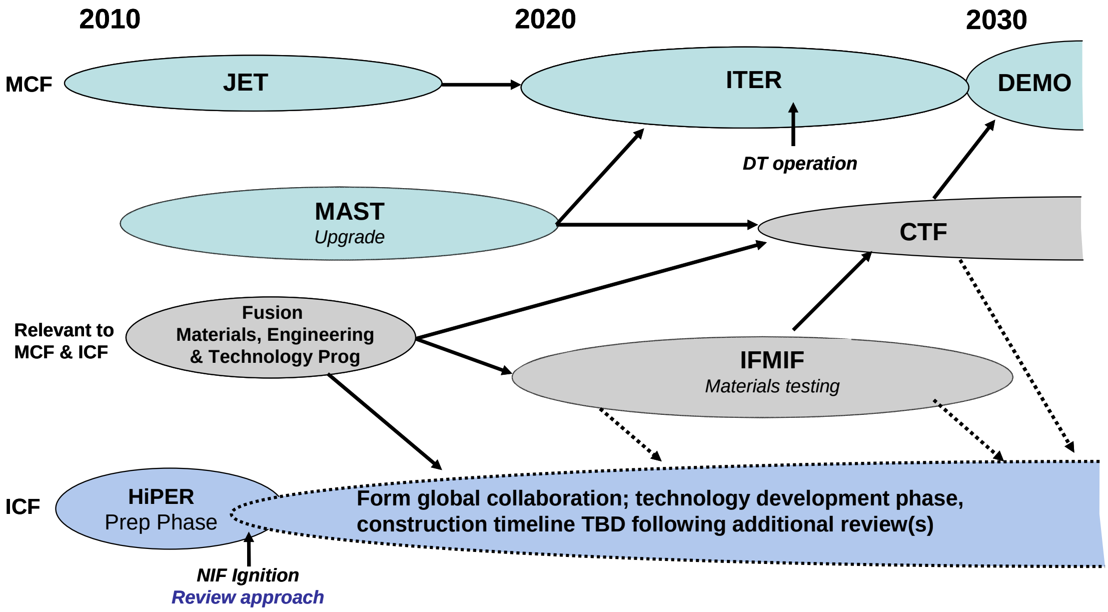
In magnetic confinement fusion (MCF) the continued exploitation of JET, particularly through its ITER-like wall (~2011) and a proposed tritium campaign (~2013) mean that it is still highly relevant for validating ITER physics issues. However, towards the end of the next decade, JET will have closed, or be winding down, and global attention will turn to ITER as the next stage of the fusion “fast track” commences, but ITER alone will not be sufficient to realise fusion power and technology and materials development will also be crucial.

Through an upgraded MAST, the UK can play a leading role in the development of a Component Test Facility (CTF) which may be important in reducing the risk for construction of the fusion demonstration reactor (DEMO), the step following ITER.

The role for the UK in inertial confinement fusion (ICF) over the next 20 years is strongly tied to what happens at the US Department of Energy’s National Ignition Facility (NIF) in the next 2-3 years. The UK has displayed an impressive capability in coordinating the European ICF area through its leadership of the HiPER project and it would be most effective if this were to develop into a global collaboration to develop a plan to exploit NIF ignition towards fusion energy.

The UK should continue to contribute to world-class research and international leadership in both MCF and ICF, particularly developing the technology pathway. We should maximise opportunities for global collaboration and develop a common programme between MCF and ICF in fusion materials, engineering and technology development.

An international fusion materials programme would enhance synergies between MCF and ICF, as well as nuclear fission, and tie in with the proposed International Fusion Materials Irradiation Facility (IFMIF).



Possible High-level Pathway for UK Fusion for Energy

1 INTRODUCTION

In August 2009 EPSRC and STFC convened an Expert Group to assist in developing a 20-year vision for UK fusion for energy.[1] The terms of reference and membership of the group are given in Annex A. The input that the Expert Group received included existing roadmaps, strategies and reviews from across the world covering both magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) - the full list of which is given in Annex B. An online survey consultation ran from 14 August until 18 September and received 87 responses that were fed into the Expert Group – the questions asked are given in Annex C. Two meetings of the Expert Group were held in October; the first of these focussed on the UK MCF and ICF communities' visions for the next 20 years, while the second sought an international perspective from Europe, Japan, the United States and the UK.

This document provides the commentary that underpins the Expert Group's 20-year vision for fusion as an energy source. Throughout their discussions the Expert Group were mindful of the economic outlook for the Research Councils at the current time.

2 CURRENT INTERNATIONAL PATHWAY TO FUSION AS AN ENERGY SOURCE

In the next 20 years the pathway to MCF is dominated by the "Fast Track to Fusion" which is signed up to by many countries worldwide, shown in Figure 1. The Fast Track, which the Culham Centre for Fusion Energy (CCFE)[2] was instrumental in getting approved by EURATOM, occurs in well-defined steps towards a demonstration reactor (DEMO). The focus of MCF activity worldwide will shift from the UK-operated Joint European Torus (JET), currently the largest magnetic fusion device in the world and one of only two devices in the world to have achieved fusion power (in 1997 JET produced 16MW of fusion power from a total input of 24MW), towards the ITER facility. ITER will be the first device to release reactor-relevant fusion power (~ 500 MW 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. ITER will be built in Cadarache, France by the ITER partners Europe, USA, Japan, Russia, China, Korea and India. ITER is the culmination of many decades' endeavour to realise controlled nuclear fusion on the basis of magnetic confinement and represents the crucial test of its scientific and conceptual basis. ITER is currently due to start operation in 2018 with another key milestone being the first deuterium-tritium (D-T) operation at ITER scheduled for 2026. Towards the end of the 20-year horizon, attention will be turning towards DEMO, but preparatory work will need to start well before this.

In the case of ICF, the world is watching and waiting for ignition (using lasers to compress D-T filled capsules and produce net energy gain) to occur at the US Department of Energy's $3.5Bn National Ignition Facility (NIF). Ignition is expected with high confidence to be demonstrated in the late 2010 through 2012 timeframe. While a variety of inertial fusion energy schemes have been proposed in the UK, France, Japan, and the US, there is currently no coherent international plan for the exploitation of NIF ignition from an energy perspective, partly because until now much of the driving force behind ICF has been defence related. This situation is now changing, with the advent of proposed energy-related activities in the EU and Japan and the November 2009 announcement by the US of a National Research Council study on the implications of NIF ignition for inertial fusion energy. The current situation represents an opportunity for the preparatory phase of the UK-led HiPER project, the approach for which is wholly unclassified and civilian, to shape a future global collaboration.

[1] For an introduction to what fusion is see Annex D.

[2] Following the sale of UKAEA Ltd to Babcock International Group in October 2009 UKAEA Culham is now called the Culham Centre for Fusion Energy (CCFE).

As with most long-term programmes, there are still risks and uncertainties in MCF and ICF that may affect the timescales in the pathways.

2.1 Magnetic Confinement Fusion

The main "Fast Track" line is from JET through ITER and DEMO to commercialisation. There is complete agreement within the EU over these main steps. However, there is some contention as to how best to realise the technology side of the Fast Track. The requirement to test fusion materials in advance of DEMO is recognised by the need for an International Fusion Materials Irradiation Facility (IFMIF) that is being progressed as part of the "Broader Approach" between the EU and Japan. IFMIF will only be able to test small samples of material; it won't be able to test components for fusion reactors. In the standard Fast Track, components such as the breeding blanket would only be fully tested for the first time in DEMO. This is seen by some as a high-risk approach and some early qualification of components in a Component Test Facility (CTF) is proposed to reduce the risk. A spherical tokamak, such as MAST (Mega Amp Spherical Tokamak), the main domestic experiment of the CCFE (and its sister experiment NSTX in the USA), is a leading candidate to test the feasibility of a CTF. The expected results from MAST and NSTX are critically needed to inform the design of a CTF concept.

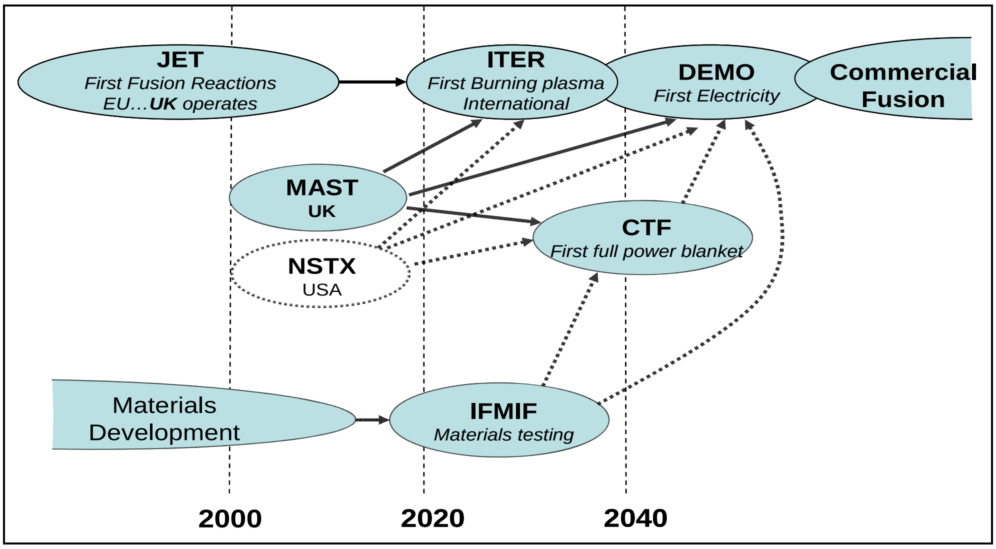


Figure 1: International pathway to magnetic fusion

Finding: *The magnetic confinement development is proposed to occur along the plan shown in Figure 1. There is not yet full international agreement on the fusion technology development path. The timelines and preferred approach for IFMIF and particularly CTF are not fully specified yet.*

2.2 Inertial Confinement Fusion

ICF activities are ongoing in a number of nations, including the UK, France and other EU countries, the US, Japan, Russia and China. The next and critical step in the path to inertial fusion energy is the achievement of ICF ignition. Ignition is the central goal of the National Ignition Facility (NIF) and Laser Megajoule (LMJ), defence-funded ICF facilities located in the US and France, respectively. NIF construction was completed in March 2009, and LMJ will start its physics programme in 2014. The next few years will be critical for inertial fusion energy, as the ignition scientific program at NIF, a US effort that also involves France and the UK, is well underway. The first ignition experiments at NIF are expected in the third quarter of 2010. Hence, it is appropriate for the UK and other nations to commence planning for future inertial fusion activities that leverage the demonstration of ignition.

The UK has shown strong leadership by proposing the first plan for international cooperation in developing inertial fusion energy. This European plan, known as HiPER (**Hi**gh **P**ower laser **E**nergy **R**esearch) is in the preparatory phase. Figure 2 tries to summarise the HiPER fusion pathway along with other complementary laser facilities that either underpin or feed into HiPER development and the required MCF materials developments that are also required for ICF. The expert group recognises this pathway as the vision of the HiPER project, but does not endorse the details or the specific dates. Generally, the path to fusion energy via ICF is at least comparable in challenges to that via MCF.

Finding: *While individual schemes for inertial fusion energy have been proposed, there is no clear international plan to develop inertial fusion as an energy source. The HiPER project appears to be the most advanced international collaborative effort but may not be sufficient on its own.*

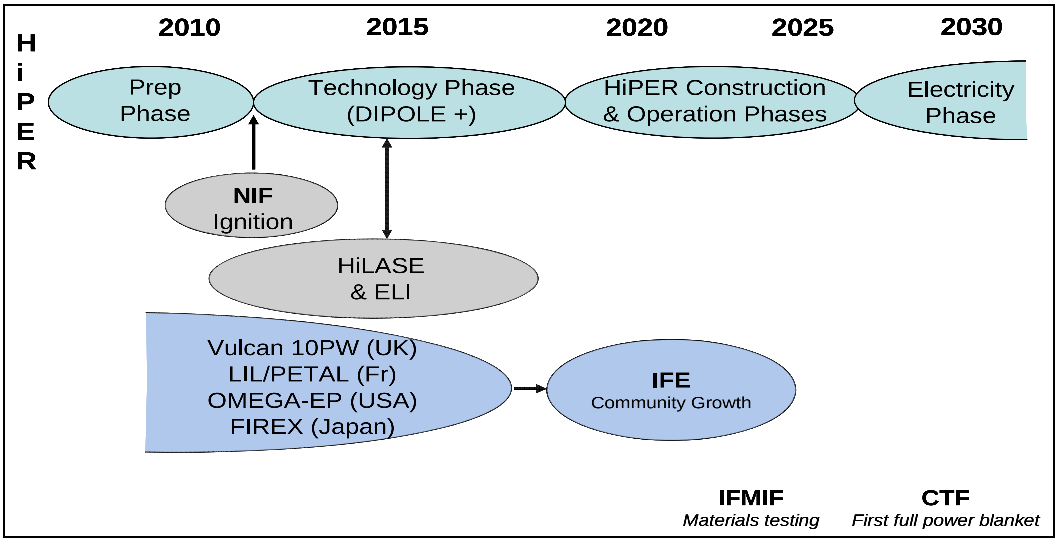


Figure 2: HiPER pathway to inertial fusion energy

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 MCF

The UK has played an internationally leading role in the development of MCF for over 50 years. This has included the operation and exploitation of the world's leading fusion facility, JET, at the CCFE and the development of the spherical tokamak approach from START (Small Tight Aspect Ratio Tokamak) through to MAST. UK expertise in tokamak operations, engineering, and fusion physics, developed under JET, will be essential to the success of ITER. This strength in facility operation is complemented by a leading experimental and theory programme, much of which is carried out in collaboration with universities and international partners. In the next 5-10 years JET will close and the focus of MCF will switch to ITER. 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 short term. Specific highlights will be the completion of the ITER-like wall (~2011) which will lead to experiments that will improve ITER's performance and reduce the risk for ITER. The next JET tritium campaign is planned for ~2013 and should set new fusion power records.

Barriers to achieving this surround the continued uncertainty over funding that could lead to the early closure of JET.

Finding: *The world-leading JET facility is needed until ITER is sufficiently advanced that JET operational and other expertise is no longer required to assure the success of the ITER Project. Increases in ITER costs are putting pressure on the JET budget; however, continued operation of JET over the coming years is crucial to the success of ITER.*

3.1.2 Development of an International Test Bed for a CTF

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.

The proposed CTF is potentially an important part of this effort. Apart from funding, potential barriers to achieving this include the lack of a clear international view on the need for a CTF presently limiting international collaboration and contributions. It would be highly desirable to have international collaboration specifically as the CTF development would need a global approach. There is a developing discussion amongst potential partners of the need for a CTF-like fusion nuclear facility in the world programme, and an active lead from the UK and EU could influence the directions of such discussions.

The concepts offered for a CTF are 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 an upgraded MAST could be critical to this discussion. This would position the UK as a leading player in determining the direction of this potentially crucial component of the international MCF strategy. If the spherical tokamak proves to be the best approach then an upgraded MAST would be a major contribution to expediting this strategy. MAST is the only machine in the world that can fit the so-called super-X divertor. This component of the exhaust system is needed for dealing with the divertor heat load which is specifically crucial in spherical tokamaks but affects **all** tokamaks. The super-X divertor would enhance the potential of spherical tokamaks to contribute also to the main line in critical development areas.

Finding: *While the Expert Group recognises the value of a CTF there is not yet consensus on the need for a CTF in the international pathway. Culham advocates this from a risk reduction point of view for DEMO and there is support within the US for this position. The decision process within Europe has been initiated by the Fusion Facilities Review Panel but because of the present orientation toward ITER, the debate as to whether a CTF is necessary to sufficiently mitigate risk or merely desirable for the smooth licensing of fusion power stations, is pending. The results from a MAST upgrade could have significant influence on the outcome of these discussions.*

3.1.3 Theory, Modelling, Materials and Engineering Development

Theory, modelling, materials and engineering development underpins activities at JET, ITER, MAST and in technology development and have been a key element of the UK fusion programme in recent years. A particular strength has been the development of links between Culham and the academic community and as fusion moves more towards materials, engineering and technology problems, academic collaborations in these areas should also be pursued.

Opportunities exist to develop links between MCF and ICF in areas such as first wall design and blanket technology that need to be optimised in the coming years. Work in this area will be of value to IFMIF, where characterisation and qualification of candidate structural and functional materials which will be needed to construct DEMO, will take place. There are also synergies with advanced fission systems.

There are also opportunities to develop international links on all of these issues.

Finding: *Increased attention on materials, engineering and technology issues is required for the success of both MCF and ICF. There are synergies between MCF and other fields such as ICF and nuclear fission that could enhance overall capability if they were developed. There is a focus on these issues developing internationally.*

3.1.4 Magnetic Confinement Fusion for Industry

ITER is a multi-billion euro construction project and UK companies (such as Jacobs, Atkins, Halcrow, Oxford Instruments and Oxford Technologies) are already benefiting from contracts placed by the ITER Organisation and F4E (Fusion for Energy).

In the next 20 years, opportunities for UK industry include:

- Remote handling technologies
- Superconductor technology
- Tritium handling
- Diagnostics
- Control and data systems
- Materials
- Blanket design and testing – i.e. tritium breeding and power conversion technologies (common to MCF and ICF).

Barriers to industry involvement include:

- A lack of awareness of SME opportunities within ITER
- The EU approach to IPR may discourage business (common to MCF and ICF)
- UK companies' R&D budgets are not focussed on very long term returns (common to MCF and ICF).

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 and the interaction of radiation with matter. With the construction and operation of the VULCAN laser, and upgrades, at RAL, together with the HELEN and now ORION lasers at the Atomic Weapons Establishment (AWE), the UK is also a leader in the construction and operation of high-energy, high-power inertial fusion facilities.

The advent of HiPER and the ignition programme at NIF motivate a rethinking of the missions underlying laser-plasma research in the UK and the role of inertial fusion in the UK fusion programme. The recommended near-term strategy is to focus the HiPER effort on the development of a detailed UK and international plan for inertial fusion energy contingent upon the successful achievement of ignition at NIF.

The UK has developed the HiPER project to build a team and a plan to advance inertial fusion energy following achievement of ignition at NIF. The HiPER Project is currently in a three-year preparatory phase. Following the preparatory phase (and pending successful ignition at NIF), the next stage is a seven-year technology phase which would be followed by construction of HiPER. It is HiPER's vision that the balance of funding would move away from public funding and towards investment and industry funding during the technology and construction phase; however, this view was challenged by the Expert Group as being unrealistically optimistic (see comments in section **4**) and merits further scrutiny (see Recommendation **3**).

Finding: *Historically the UK has not had a clearly defined programme in inertial fusion energy nor a unified fusion strategy. Recent activities in the HiPER project now present a coordinated development path in inertial confinement fusion. The UK now needs an integrated approach at a national level to determine how to take forward our overall fusion strategy.*

3.2.1 Collaboration

If NIF ignition occurs, this will be a seminal moment in the development of inertial fusion. What comes after NIF ignition is then the key question and one for which there is currently no clear international answer. This presents an opportunity for the UK to use its role in coordinating the HiPER preparatory phase to turn it into a truly global endeavour. Such a collaboration should leverage the UK's key assets in this field (RAL, universities, AWE, MoD). There are also synergies between MCF and ICF such as first wall design and blanket technology that could be optimised in the coming years.

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 in the next two to three years, 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.

There are common elements in theory, modelling and materials development, referred to in ***3.1.3***, for MCF that are also applicable to ICF.

Finding: *There is currently no coherent international plan to exploit NIF ignition and an opportunity certainly exists for the UK to be involved in developing this through the HiPER preparatory phase.*

3.2.2 Inertial Fusion for Industry

UK industry has significant expertise in laser construction based most recently on construction of the ORION laser at AWE. Should NIF ignition succeed and a next-step inertial fusion facility be constructed, opportunities for UK industry include:

- Conventional facility construction (specific to high-energy lasers)
- Integrated computer and control systems
- Laser technologies and large-scale integrated laser systems
- Optics technologies
- Diagnostics and high-speed photonics
- Remote handling technologies
- Tritium handling
- Blanket design and testing – i.e. tritium breeding and power conversion technologies (common to MCF and ICF).
- Target fabrication, injection and handling.

Barriers to industry involvement include:

- The lack of an agreed roadmap
- The EU approach to IPR may discourage business (common to MCF & ICF)

- UK companies' R&D budgets are not focussed on very long-term returns (common to MCF and ICF).

Many in the inertial fusion community believe it is possible to bring a DEMO-like facility and eventual wide-spread implementation of fusion power approximately 10-15 years earlier than MCF. This assertion does not benefit from the same level of analysis and experience as the Fast Track proposal for MCF and the Expert Group believes it cannot be accepted without substantial further rigorous study.

The relative timeline for implementation of ICF, and its comparison to the MCF timeline, is not clear and requires further analysis and review. A detailed technical review of proposed inertial fusion power production timelines should be undertaken as part of the review process discussed in Recommendation **3**.

3.3 Skills and Capability

3.3.1 MCF

In recent years there has been significant strengthening of the relationship between CCFE/Culham and the UK university base which is training the next generation of fusion scientists and engineers. In order to provide the skills required to achieve the fusion Fast Track, this investment needs to be sustained. Currently, Culham have a PhD student cohort of 42 students (for which they provide some funding) spread roughly between three areas: plasma and related physics (28); materials science (4); and engineering and technology (10). These students come from 16 different universities with half being based at Culham 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 Culham.

As JET operator, Culham also has unrivalled hands-on experience of fusion technology which 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, Culham also has expertise in designing and building fusion facilities that would be required for any MAST upgrade.

3.3.2 ICF

The UK has successfully constructed and operated the VULCAN and HELEN lasers at RAL and AWE respectively, and more recently has embarked on the construction of the £100M ORION laser at AWE. The ORION system will be one of the premier high-power, high-energy lasers in the world and will be open to both the national security and academic research communities. 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.

However, there is currently a lack of sufficiently trained personnel for the UK to develop the materials, engineering and technology required to make HiPER a reality on its own. 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.

4 INDUSTRIAL ENGAGEMENT WITH FUSION ENERGY

Industry interest beyond 2030 (in fact beyond 2050) will be different from that in the next 20 years. It will move from development and construction of facilities such as JET and ITER towards a demonstration power plant. Companies that you might associate with building a fusion power plant (such as Siemens, GE, Areva) currently have little or no involvement in fusion due to the long timescales to, and uncertainty over eventual, commercial viability. There is no imperative for them to be involved at present, and no risk of them being excluded from future commercial exploitation if they are not. Should fusion be demonstrated to be potentially commercially viable, it is very likely that only these large, financially robust organisations could credibly undertake the development and supply of commercial reactors. It may be the case that, as in other fields, they will acquire the required skills and capability to build fusion power plants by buying those firms that have them rather than developing them in house.

It must be remarked that no accepted scenarios for the energy system in 2050 include any contribution from fusion technology. It is thus improbable that any commercial organisation will invest its own R&D resource in such a speculative area when they have pressing needs to develop new products that are foreseen in all scenarios, and for which there is already demand, such as carbon capture and storage (CCS), offshore wind, bioenergy systems and solar technologies. Industry's role is thus likely to be as a specialist (funded) developer and supplier of equipment to these large and complex experiments, but not as an investor in them.

Finding: *Outside the fusion community, fusion does not currently appear in any generally accepted energy system scenarios for 2050. Should it be successfully developed it could, after 2050, represent a highly attractive alternative to other major base-load electricity generation technologies, especially CCS-equipped fossil fuel plants or nuclear fission reactors which are expected to play the major role for most of the current century.*

5 DISADVANTAGES AND RISKS OF THE UK NOT BEING INVOLVED IN THE DEVELOPMENT OF FUSION AS AN ENERGY SOURCE

The major risks and disadvantages of the UK not being involved were identified as:

- Loss of skills, expertise and capability in the UK
- Loss of scientific leadership and credibility
- The UK would need to buy in the technology at a later stage
- It would not be possible to exploit ITER even though the UK would still be contributing to EURATOM
- Damage to reputation
- Potential loss of confidence in fusion (MCF and ICF) internationally if UK pulls out
- UK will be left behind once NIF ignition occurs.

The UK experience in nuclear fission provides a valuable lesson where, having decreased investment in the 1990s, we are now struggling to provide the skills and capability required to build and operate the next generation of nuclear power stations – the same thing could happen with nuclear fusion.[3]

6 RECOMMENDATIONS

1 It is clear that JET and ITER are inextricably linked. EURATOM and the ITER collaboration should develop a consistent budget plan that allows for JET operation for as long as is needed during ITER construction.

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[3] For more details see: Innovation, Universities, Science and Skills Committee - Fourth Report: Engineering - turning ideas into reality

2 The Expert Group supports the development of a common international roadmap to a CTF and recommends that the UK should push for this to be on the basis of a spherical tokamak concept. In order to further advance the spherical tokamak concept and expeditiously inform decisions for a CTF, the UK should pursue the MAST upgrade, preferably in the context of an international collaboration.

3 The UK should use its position as the co-ordinator of the 10-nation HiPER project to play a leading role in the development of a global collaboration to exploit NIF ignition. In the near term HiPER effort should focus on the development of a detailed UK and international plan for inertial fusion energy contingent upon the successful achievement of ignition at NIF. The UK should also maintain core competencies in inertial fusion and related high-energy density science during this period. A more detailed technical review should be held, whose implementation should be contingent on NIF ignition, to examine the role and future for a UK inertial fusion energy programme and should re-evaluate the schedule and predicted funding model.

4 The UK should implement a fusion (MCF and ICF) materials, engineering and technology programme in the near term. The programme may be moderate but it will be important in order to optimise UK skills and expertise in this area of developing importance. The UK should discuss opportunities for such a programme with international partners.

Annex A: Expert Group Membership and Terms of Reference

Expert Group Membership

Prof Keith Burnett (Chair)	Vice-Chancellor University of Sheffield (Member of STFC Council)
Philip Sharman	Director Technology External Affairs of Alstom Power
John Loughhead	Executive Director UK Energy Research Centre
Prof John Chapman	Dean of Physical Sciences University of Glasgow
Prof Carlos Alejaldre	Deputy Director General ITER (Member of Fusion Advisory Board; Member of HiPER Executive Board)
Prof Raymond Fonck	University of Wisconsin-Madison (Member of Fusion Advisory Board)
Prof Fritz Wagner	Max Planck Institute for Plasma Physics (Member of Fusion Advisory Board; Chair MAST Programme Advisory Committee)
Prof Francis Kovacs	Associate Director Cadarache, CEA France (Member HiPER Executive Board)
Dr Christopher Keane	Assistant Principal Associate Director and Director, National Ignition Facility (NIF) User Office Lawrence Livermore National Laboratory

Terms of Reference

The Expert Group was invited to:

1. Examine the current international pathway to fusion (both inertial and magnetic confinement fusion) as an energy source based on currently available national and international strategies, roadmaps etc.

2. Describe the potential opportunities and barriers for (i) UK research and (ii) UK business to play a leading role in the development of fusion as an energy source over the next 20 years.

3. Evaluate the disadvantages and risks to the UK of not being involved in the development phase of fusion as an energy source.

4. Using different levels of funding for illustration, provide a recommendation to the Research Councils on what the fusion for energy priorities should be for the UK over the next 20 years.

Annex B: Evidence Base Consulted

Document	Author / Origin
R&D Needs and Required Facilities for the Development of Fusion as an Energy Source - Report of the Fusion Facilities Review Panel.	European Commission http://ec.europa.eu/research/energy/pdf/978-92-79-10057-4_en.pdf
Culham's 20-year Vision for MCF in the UK	Culham
Report from Culham for EPSRC 2006 Review of UK Fusion Programme.	Culham
EPSRC 2006 Review of UK Fusion Programme.	EPSRC
Report from Culham for EPSRC 2007 Review of UK Fusion Programme.	Culham
EPSRC 2007 Review of UK Fusion Programme.	EPSRC
2007 FESAC Report - Priorities, Gaps and Opportunities: Towards a Long Range Strategic Plan for Magnetic Confinement Fusion.	US Department of Energy Fusion Energy Sciences Advisory Committee
Executive Summary of the 2008-09 Annual Report from UKAEA Culham.	Culham
Draft 2010 RCUK Large Facilities Roadmap.	Research Councils UK http://www.rcuk.ac.uk/cmsweb/downloads/rcuk/publications/Draft2010LFroadmapforconsultation.pdf
2003 Report to FESAC Committee of DoE on Development of Fusion Energy.	US Department of Energy Fusion Energy Sciences Advisory Committee
European Roadmap for Research Infrastructures (ESFRI) Report 2006.	European Commission ftp://ftp.cordis.europa.eu/pub/esfri/docs/esfri-roadmap-report-26092006_en.pdf
Culham Finance and Manpower Summary.	Culham
EPSRC Council Paper July 2009.	EPSRC
Fusion Advisory Board Minutes, July 2009.	EPSRC
FESAC 2004 Inertial Fusion Energy Program Review.	US Department of Energy Fusion Energy Sciences Advisory Committee
Response from DoE to FESAC 2004 IFE Review.	US Department of Energy
RAL's 20-year Vision for ICF.	RAL, STFC
Background information on HiPER funding.	STFC
US Congressional General Accounting Office Report 2007.	US GAO

Annex C: Consultation Questionnaire

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

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

Q3. What do you see as the opportunities for UK businesses in magnetic confinement fusion over the next 20 years?

Q4. What do you see as the barriers for UK businesses in magnetic confinement fusion 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 confinement fusion over the next 20 years?

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

Q7. What do you see as the barriers for UK research playing a leading role in inertial confinement fusion 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 confinement fusion 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 confinement fusion 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?

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 “donut” 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 tons of coal). A commercial fusion power station will use the energy carried by the neutrons to generate electricity. The neutrons will be slowed down by a blanket surrounding the machine, and the heat this provides 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 “fast ignition” approach to inertial confinement fusion examined by the HiPER project involves compressing a tiny pellet of deuterium-tritium fuel with lasers, or radiation, to high density for a short period of time. Raising the fuel to high densities forces more particles to interact with each other than at solid density. A very high power laser is then focused into the dense D-T fuel, raising it to fusion temperatures. The neutrons produced are absorbed in a surrounding blanket and the heat this provides will drive conventional steam turbines.

[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

In the UK this work is being led by STFC’s Central Laser Facility at the Rutherford Appleton Laboratory through the HiPER project and is funded by STFC and the European Union.