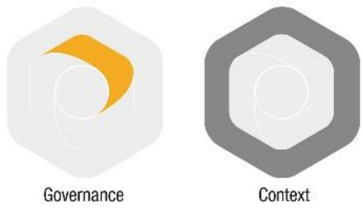
Chapter 11. Fusion



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11.1 Fusion Basics

Fusion is the process that powers the Sun and other stars. In the Sun, hydrogen nuclei fuse to form helium nuclei with a release of energy. Some of the mass of the fusing nuclei is converted to energy in the reaction. Fusion can be viewed as the opposite of nuclear fission where a heavy nucleus splits apart to produce two lighter nuclei.

Fusion in the centre of the Sun takes place at very high temperature around 15 million K and extreme pressure due to the Sun's immense gravity. At this temperature matter becomes ionised and exists in the form of a plasma. Extreme conditions are needed for fusion due to the Coulombic barrier arising from the repulsion of two positively charged nuclei. The effects of the Sun's gravity cannot be simulated on earth so even higher temperatures are required for artificial fusion.

An overview of basic fusion physics is provided on the IAEA website [1]. There is also an IAEA Fusion Portal that provides access to several fusion information booklets [2]. The IAEA has also produced in 2012 a graduate level publication on fusion physics [3].

11.2 Advantages of Fusion

Fusion power has the potential to be a new large-scale, sustainable and carbon-free form of energy. It requires the development of fusion reactors where the heat produced from fusion reactions is used to generate electricity. This is particularly important in a world needing to meet the challenges of climate change and sustainable development. The particular advantages of fusion are:

- Efficient energy production. For a given mass of fuel, fusion is capable of producing around four million times more energy than a chemical reaction involving a fossil fuel such as oil or gas and around four times as much energy as a fission reaction.
- Sustainability. Fusion fuels are abundant and widely available. Deuterium can be extracted from water and tritium can be produced from lithium in a fusion reactor.
- Carbon-free. No carbon dioxide is produced in a fusion reaction.
- No long-lived radioactive wastes. The fusion reaction, unlike fission, does not produce radioactive products. Radioactive wastes only arise by neutron activation of reactor materials. The amount of radioactive waste generated can be minimised by careful selection of reactor construction materials.
- Low proliferation risks. Fusion does not require fissile materials like uranium and plutonium.
- No risk of a major nuclear accident. A Fukushima-type nuclear accident is not possible in a fusion device such as a tokamak. A problem in a fusion reactor leads to the plasma cooling and the reaction stopping. There is only a limited quantity of fuel present at any one time and no risk of a chain reaction.
- Fusion reactors will be able to supply reliable baseload power. Renewable forms of power such as solar and wind are currently unable to meet this requirement.
- The amount of land required for power production is low compared to other forms of carbon-free energy.

11.3 Challenges to Development of Fusion Power

There are significant challenges to producing power from fusion. In particular:

1. Efficiently confining the fuel at very high temperatures.
2. Identifying and manufacturing suitable reactor wall materials due the damage caused by the energetic neutrons generated in fusion reactions.
3. Exhausting extreme heat fluxes.
4. Breeding and handling tritium. Tritium is radioactive and has a relatively short half-life (12.32 years). Tritium to fuel fusion reactors will need to be produced in the reactor by neutron irradiation of lithium and then processed for use as fuel.
5. Fusion reactors will become radioactive due to neutron activation. Remote maintenance will need to be carried out to ensure the reactor availability is high. Long shutdown periods would have implications for the economic viability of fusion power production.

The challenges to fusion power development have been examined in more detail by Chapman and Morris (2019) [4].

11.4 Fusion Research and Development

The most feasible fusion reaction on earth involves the reaction of deuterium with tritium as described in the equation below:

$$ {}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

Large specialist facilities and high levels of input energy are required for controlled fusion. The three basic conditions are:

- temperatures around 150 million K;
- sufficient plasma particle density; and
- sufficient confinement to hold the plasma and to enable the fusion reactions to take place on an ongoing basis.

Various plasma confinement concepts have been investigated. The leading designs are:

- Magnetic confinement in tokamaks; and
- Inertial confinement by use of lasers.

The most developed approach is the use of tokamaks. A tokamak is a device which uses a powerful magnetic field to confine plasma in the shape of a torus. The first tokamak (T-1) began operation in Russia in 1958. The name arises from the acronym for toroidal chamber with magnetic field in Russian.

Key components of a tokamak include:

- **Vacuum Vessel** – a ring-shaped chamber to provide the high vacuum conditions needed to produce high performance plasmas.

- **The Magnet System** – two sets of magnetic coils, toroidal and poloidal, create a "magnetic cage" to confine and shape the plasma.
- **The Divertor** – shaves off outer layer of the plasma to exhaust excess heat and remove helium "ash" and contaminants.
- **The Plasma Facing Wall** – protects the vacuum vessel and components from damage.
- **The Heating Systems** – to help to bring the plasma to fusion temperatures.
- **The Cooling Systems** – to control the temperature of tokamak structures and magnets.
- **The Plasma Diagnostics** – to measure the plasma density, temperature and emission.

The world's largest tokamak ITER (International Thermonuclear Experimental Reactor) is currently being built in the South of France. One of ITER's goals is achieve a "fusion gain" of 10. The "fusion gain" is the ratio of the power produced via fusion reactions to the power directly heating the plasma and is designated by the letter Q. More details about ITER and its goals are provided on the ITER website [5]. The website also contains images of ITER and a description of key components and a summary of international tokamak research.

The National Ignition Facility (NIF) in the US has the goal of achieving self-sustaining fusion using inertial confinement. More information about NIF is provided on the Lawrence Livermore National Laboratory website [6].

An overview of major fusion research activities across the world is provided in the World Nuclear Association (WNA) article on Nuclear Fusion Power on the WNA website [7].

Research has been carried out for over 50 years but it has not been possible to achieve a net power gain until very recently [8]. One of the key goals of current fusion research and development activities is to reach the point at which the fusion reaction becomes completely self-sustaining

The Culham Centre for Fusion Energy (CCFE) [9] is the UK's national laboratory for fusion research. CCFE is one of EUROfusion's participating laboratories. EUROfusion is a consortium of national fusion research institutes located in the European Union, Switzerland and Ukraine. EUROfusion funds fusion research activities in accordance with the Roadmap to the realisation of fusion energy. [10].

Current Roadmap activities include:

- Operation of the Joint European Torus (JET) [11];
- ITER construction; and
- the conceptual design of a demonstration power plant (DEMO).

DEMO will be the successor to ITER and the final step before the construction of a commercial fusion power plant, see Figure 1.

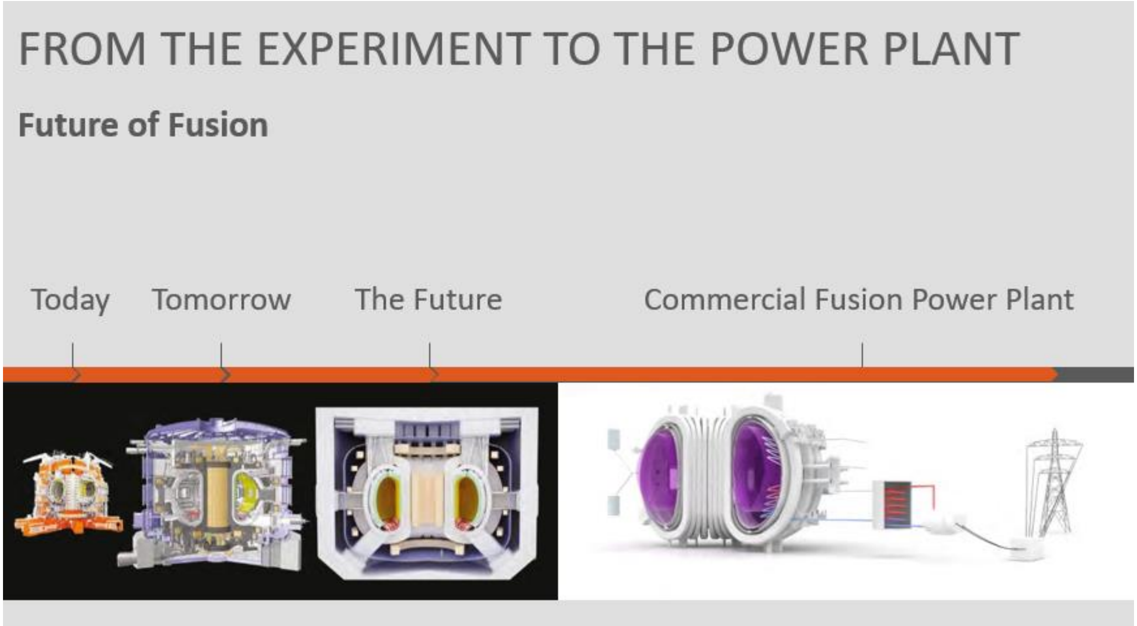


Figure 1 EUROfusion Route from JET to Commercial Fusion Plant

CCFE is based at the Culham Science Centre in Oxfordshire. The site is operated by the UK Atomic Energy Authority (UKAEA). The site was originally called Culham Laboratory and opened in 1965. Various fusion concepts have been explored at Culham but from the 1970s onwards work has focused on magnetic confinement using tokamaks.

Culham was chosen as the site for the JET tokamak in 1977. JET is a conventional "doughnut shaped" tokamak, see Figure 2.

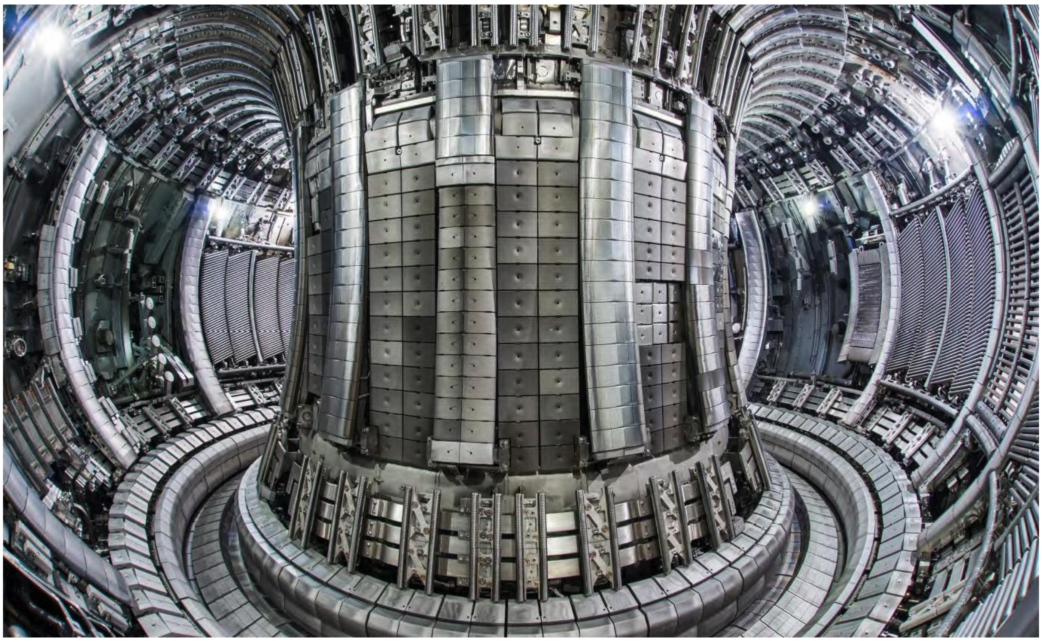


Figure 2 Interior View of JET

JET operations began in 1983. JET has made a significant contribution to advancing the science and engineering of fusion, in particular;

- Carrying out the world's first fusion experiments using a mix of tritium and deuterium.
- Setting world records for fusion performance;
  - Achieving the closest approach to power breakeven in tokamak in 1997 with a Q value of 0.67.
  - Achieving the most energy produced in a single fusion shot in 2021.
- Remote handling developments enabling replacement of certain components including the installation of an "ITER-like" plasma facing wall made of beryllium and tungsten.

Initially JET was run by a multi-national team but since 2000 it has been run by UKAEA. JET is one of the main the main test machines for ITER. Completion of JET's final test campaign is scheduled for the end of 2023. A JET Decommissioning and Repurposing (JDR) programme is planned [12]. JDR will involve the first-of-a-kind decommissioning of a tritiated fusion reactor. It will be one of the biggest decommissioning projects in the UK.

Since the 1980s Culham has played a significant role in the development of spherical tokamaks. The plasma in a spherical tokamak is held in a cored-apple shape. There are potential advantages to the spherical design that could lead to smaller and more efficient fusion reactors including modular reactors. START (Small Tight Aspect Ratio Tokamak) was operated at Culham between 1991-1998. A larger device called MAST (Mega Amp Spherical Tokamak) was then built and operated between 2000 and 2013.

MAST has been rebuilt and is now known as MAST Upgrade [13]. The MAST Upgrade facility is leading the world in research into compact fusion devices. The main objectives of the MAST Upgrade programme are:

- Add to the knowledge base for ITER;
- Test innovative plasma exhaust systems (known as the divertor); and
- Explore the case for a future fusion reactor based on a Spherical Tokamak.

The STEP (Spherical Tokamak for Energy Production) programme [14] was announced in 2019. The programme has the aim of designing design and building the world's first compact fusion reactor by 2040. The UK Government is providing initial funding of around £220 million to cover the initial five-year concept design phase. A detailed engineering design phase will follow with the construction phase expected to start in 2032. The ultimate aim is to produce net electricity from fusion around 2040.

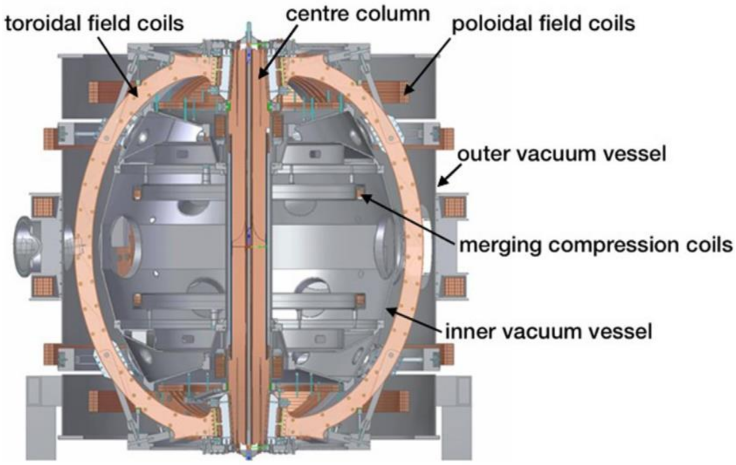
Other important fusion related activities being carried out by UKAEA include:

- The recently opened Materials Research Facility (MRF) at Culham investigates the effects of irradiation on materials;
- Robotic and remote handling technology developments at the Remote Applications in Challenging Environments (RACE) centre at Culham;
- Tritium handling with the new Hydrogen-3 Advanced Technology (H3AT) facility due to open by 2022 at Culham;
- The opening of a new fusion technology centre near Rotherham, South Yorkshire;
- A training centre, Oxfordshire Advanced Skills (OAS), enabling Oxfordshire business to offer young people hi-tech and engineering apprenticeships of the highest quality; and
- Advances in computing technology to support fusion research.

More details about UKAEA facilities and activities are available on the CCFE website.

UK fusion research and development is also being carried out in the private sector, in particular:

- Tokamak Energy Ltd is developing compact and efficient fusion reactors by combining two emerging technologies: spherical tokamaks and high field magnets made from high temperature superconductors. The company is seeking to demonstrate the feasibility of fusion as an energy source in the 2030s. It received a £10m Government grant from the Advanced Modular Reactor competition. A drawing of a spherical tokamak (ST 40) developed by Tokamak Energy is shown in Figure 3. More details are available on the Tokamak Energy website.[15].
- First Light Fusion Ltd, a spin-off from Oxford University, is researching energy generation by inertial confinement fusion. More details are available on the First Light Fusion website [16].



A. Sykes et al., Tokamak ST40 engineering drawing, CC BY 3.0

Figure 3 Drawing of Tokamak Energy ST 40 Spherical Tokamak

The UK Government has published a fusion strategy [17]. Through the implementation of this strategy, the UK hopes to lead the world on the commercialisation and deployment of fusion technology.

An overview of the state of the fusion industry is provided in the publication The global fusion industry in 2022 [18] produced by the Fusion Industry Association.

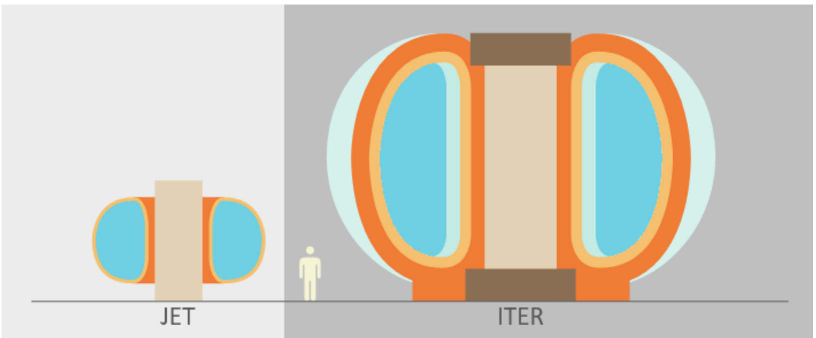
11.5 ITER Project

11.5.1 Project Overview

The origins of the ITER project [19] can be traced back to Geneva Summit between the Soviet Union and he US in November 1985. Mikhail Gorbachev and Ronald Reagan, in the press release from the Summit, advocated international cooperation in obtaining fusion energy. A joint committee was established in 1988 to work on the initial design of the machine with the participation of the Soviet Union, the United States, Europe, and Japan. In July 1992 the ITER members decided to initiate a technical design phase to create detailed plans of the machine. A detailed design of ITER was eventually completed in 2001. It was eventually agreed to build ITER in France and the ITER agreement was signed in 2006.

The ITER Project involves the construction of scientific buildings and facilities on a site the approximate size of 60 soccer fields. The total price of construction and operations is projected to be around 20 billion euros.

The ITER tokamak is probably the most complex machine ever to be built with over one million components. The tokamak has a mass of 23,000 tonnes. It is around three times as heavy as the Eiffel Tower. It will also be equipped with the world's largest ever superconducting magnets in order to sustain long plasma pulses. JET is the closest existing tokamak to a power plant both in size and in performance. ITER will be twice the size of JET in linear dimensions, see Figure 4.



	JET	ITER
Radius	3 m	6.2 m
Volume	90 m^3	840 m^3
Power factor Q	0.65	10
Fusion Power	16 MW	500 MW

Figure 4 JET and ITER Comparison

Project progress is reported on the ITER website.[20]. Figure 5 is an aerial view of the ITER site in 2020.

Figure 5 aerial view of the ITER site in 2020

11.5.2 Organisational Arrangements

The ITER Organisation was established by international treaty. The seven ITER members are; China, the European Union, India, Japan, Korea, Russia and the United States. The members signed the ITER Agreement in November 2006. The UK continues to participate in ITER post-Brexit as part of Fusion for Energy (F4E) [21]. The ITER Organisation has non-Member technical cooperation agreements with Australia; Kazakhstan and Canada. ITER involves the collaboration of 35 countries in total. The manufacturing of the most strategically important ITER components is shared among the seven ITER Members. The majority of Member contributions to ITER are provided "in-kind" by delivering components rather than transferring money.

The ITER Organisation is the nuclear licensee and is also responsible for:

- the design of the ITER Tokamak and its auxiliary systems;
- machine installation and assembly; and
- operations.

Domestic Agencies (DAs) have been created by each ITER Member. F4E acts as the DA for the European Union. The DAs are responsible for procuring the ITER components, systems and buildings that fall under each Member's responsibilities. Europe contributes around 45% including nearly all the site buildings. Each of the other Members contributes around 9%. The reason for this distribution is that Europe receives the largest amount of economic impact due to ITER being sited in France.

11.5.3 Licensing and Regulation

ITER is licensed as a Base Nuclear Installation (BNI) under French law. ITER is the first fusion device in the world to obtain nuclear licensing. The Order of 7 February 2012 [22] sets the general rules for BNIs. The ITER Organisation as licensee is required to implement and improve an Integrated Management System (IMS). The Order also requires:

- Quality requirements to be defined for each activity that is important to ensuring operating safety;
- Appropriate skills and methods to be applied to meet defined quality requirements;
- Checking of compliance with defined requirements;
- Detected deviations and significant events be corrected and preventive measures be implemented; and
- Supervision of contractors.

Implementation at ITER of the French Order of 7 February 2012 is described by Wouters et al. (2017) [23].

The ITER Organisation submitted a Preliminary Safety Report [24] in March 2010 to ASN the French nuclear safety authority and regulator. A Public Enquiry required by the 2006 French Act on Nuclear Transparency and Safety was held in 2011. The outcome of the Enquiry was favourable. An in-depth technical inspection of the ITER safety case files by ASN was completed in 2012. ITER was authorised as a BNI in November 2012. The ITER Organisation also provided a safety stress report to ASN in late 2012. Stress reports were requested from all nuclear power plants and research infrastructures in France following the Fukushima Daiichi accident in 2011.

Oversight and inspection of ITER by ASN is carried out in a manner similar to other BNIs. A framework programme for inspections and oversight has been established. The ITER Organisation send monthly lists of deviations and quarterly project progress reports to ASN. These documents inform ASN about issues that need to be included in regulatory inspections.

The majority of manufacturing for ITER is carried out off-site in the countries of the ITER members. ASN carries out inspections in these countries, where necessary, to ensure that the requirements of French law are being met. ASN initially identified inadequacies in the dissemination and adoption of the safety requirements defined by the ITER Organisation. However, more recent ASN inspections have shown a significant improvement, see ASN annual reports on the state of nuclear safety and radiation protection in France [25].

11.5.4 Safety and Environmental Management

ITER has an important role in demonstrating that fusion power is not only viable but also is safe and environmentally responsible. ITER is subject to the requirements of French laws and regulations.

Significant safety & environmental issues for ITER include:

- Maintaining containment of radioactive materials particularly tritium;
- Minimising exposure to all sources of ionising radiation including sources arising from activation of materials under intense neutron flux;
- The removal of the residual heat from the reactor compartments particularly during maintenance work;
- Minimising the amount of radioactive waste generated;
- Safely handling and storing the significant quantities of potentially carcinogenic beryllium required for the plasma facing wall and other ITER components; and
- Managing the non-radiological hazards associated with the construction and operation of ITER and its supporting facilities.

Relevant safety and environmental requirements are passed onto DAs and suppliers. Compliance is confirmed through monitoring and audit of contractors and subcontractors. The ITER Organisation is responsible for ensuring that an appropriate safety culture is established across its supply chain.

Key features of the ITER Organisation's approach to safety and environmental management [26] include:

- Rigorous approach to safety including the production of a Preliminary Safety Report of over 5,000 pages;
- Designing ITER to withstand all credible accidents including earthquake and flooding;
- Application of the "Defence in Depth" [27] approach;
- Application of the "as low as reasonably achievable" (ALARA) approach to minimising occupational radiation exposure [28];
- Provision of robust engineered barriers, for example the vacuum vessel and the concrete bioshield, to protect people and the environment from radiological hazards;
- Limiting the amount of tritium on-site;
- A multiple-layer barrier system to protect against the release of tritium into the environment;

- Advanced systems for the recovery of tritium from gas and liquids;
- Forbidding access to the Tokamak Building during operation;
- An integrated safety management system to address all potential hazards (non-radiological hazards taken into consideration include fire, exposure to magnetic and electromagnetic fields, exposure to chemicals or cryogenic fluids, and high voltages);
- A detailed beryllium safety program to ensure safe handling and storage of the metal and to prevent inhalation of potentially carcinogenic beryllium dust;
- Rigorous quality assurance and quality control to ensure that structures, systems and components meet relevant safety and environmental requirements;
- Minimising the production of radioactive waste; and
- Treating packaging and storing radioactive waste materials on-site.

Safety and environmental management arrangements are summarised on the ITER website. More details are provided in the answers to frequently asked questions and in various news articles on the website.

11.5.5 Quality Management

A Management and Quality Program (MQP) has been progressively developed since 2008. The MQP is a process-based management system that defines the overall framework for the execution of the ITER project. The MQP covers all management, safety and performance activities. The suite of highest-level MQP documents are the Project Management Plan and the Quality Assurance Program (QAP). The first issue of the QAP was produced in 2007 and was based on IAEA GS-R-3 [29] (now superseded by IAEA GSR Part 2 [30]).

The ITER project's complexity has resulted in a number of unique challenges. Delivery proved to be difficult with concerns over delays and significant cost increases. The management assessment carried out in 2013 identified leadership, management and cultural weaknesses, see [31]. An action plan was produced that was aimed at:

- Creating a "project culture" with a focus on achieving First Plasma in 2025;
- Producing a realistic project schedule;
- Instilling a strong safety culture throughout the ITER Organisation, the DAs and the supply chain;
- Aligning the interests of the ITER Organisation and DAs;
- Improving communications between the ITER Organisation and the DAs;
- Streamlining the ITER Organisation by reducing the number of Senior Managers;
- Strengthening Systems Engineering and integration;
- Reducing bureaucracy; and
- Strengthening capability and improving human resource management.

A ten-year, 174 million euro contract was signed in June 2016 with the MOMENTUM Joint Venture [32]. MOMENTUM acts as Construction Manager-as-Agent (CMA) and supervises the ITER construction contracts. The CMA is responsible for the application and adaption of industry best practice for large construction projects.

All quality-related activities (quality assurance, assessment and control) were centralized in 2018. The Safety and Quality Department reports directly to the ITER Director-General. A programme of internal and external audits is carried out that includes DAs.

11.5.6 DA Arrangements

All DAs have QAPs approved by the ITER Organisation. The F4E QAP title was changed to Management and Quality Programme [33] in 2019. The Management and Quality Programme is based on ISO 9001:2015 [34] and IAEA GSR Part 2.

Technical and management requirements are included in contracts. Some of the management requirements are in referenced F4E documents including nuclear safety, project management and quality [35]. Suppliers are required to use standard templates for some documents such as Supplier Release Notes.

A graded approach is used for procured items. The ITER Organisation's quality classification system [36] is promulgated throughout the supply chain. The Quality Class (1-4) is determined using factors related to the impact and the likelihood of item failure. Class 4 is assigned to items whose failure has no significant impact.

Quality Plans are required for all items in Classes 1-3. The Quality Plan details the quality system applied by the supplier to meet the specified contractual requirements. There are additional requirements for Class 1 and 2 items in particular:

- Design reviews and verifications;
- Submission of Inspection and Test Plans for acceptance prior to starting work;
- Submission of applicable procedures (covering manufacturing, testing and inspection, factory acceptance testing, assembly & construction) for review;
- Manufacturing Readiness Review prior to commencing manufacturing; and
- Production of a Manufacturing Dossier.

The ITER Organisation and DAs use gate reviews and control points to ensure that manufactured items meet specified requirements. Ideally any non-conformities are identified before components are shipped to the ITER site. A mechanism, the Inter-Organisation Non-Conformity Resolution Mechanism, is in place for dealing with any non-conformities identified on the ITER site.

11.6 Management System applied to UKAEA activities at Culham

The Culham site does not require a nuclear site license. The UK Atomic Energy Authority is, however, a permit holder [37] under the Environmental Permitting Regulations for the "Keeping & Use of Radioactive Materials and Disposal of Radioactive Waste".

The management system that is applied to UKAEA activities at Culham meets the requirements of ISO 9001, ISO 14001 and ISO 45001. The management system is certificated by a UKAS approved certification body against all 3 standards. It includes processes for the management of research programmes, projects and engineering including design. There are arrangements for the radiological hazard categorisation of facilities and the production of safety cases. There are also comprehensive arrangements for the management of conventional safety hazards. Operations at JET and other facilities require regular analyses for tritium and beryllium. There is an on-site laboratory that carries out these analyses that is accredited to ISO 17025 by UKAS.

The scope of the UKAEA Management System is limited to:

- Scientific Research and Engineering development in relation to controlled thermonuclear fusion, including operational facilities and the study of associated technological, economic, decommissioning, safety and environmental issues for the UK Government.
- Design management, procurement and assembly of experimental machines and equipment in support of research and development.
- Development and provision of associated specialist technical services and consultancy for UK business and fusion stakeholders.
- Management of UKAEA owned property assets, including providing services to site tenants.

This includes outsourced operations and operations completed by UKAEA people away from the UKAEA premises.

11.7 Future UK Regulation of Fusion

In October 2021, the UK government opened a consultation on fusion regulation [38] after publishing a Green Paper. In June 2022, the government published its response to the consultation. The decision [39] was that current UK regulators of fusion R&D facilities would retain responsibility for fusion. This means that future fusion facilities in the UK will be regulated by the EA and HSE (or devolved bodies as appropriate). This approach will apply to all planned fusion prototype energy facilities in the UK.

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Revisions

Revision date	Description	Contributors	Editors
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