1. Introduction

ITER has the objective of showing how magnetic confinement fusion can be used as a practical energy source. It brings together the key technologies - superconducting magnets to minimise power losses, plasma-facing components to resist high heat fluxes, remote maintenance of damaged internal components, and tritium-breeding blankets with high temperature coolants, with a powerful reactor-grade plasma. Successful ITER operation will allow nuclear fusion to be seriously considered in the energy mix from the latter half of this century. Due to its experimental nature, yet closeness to the final reactor scale, the costs and risks of such a venture are shared by all the nations with a strong programme of plasma physics research, namely the People’s Republic of China, Europe (represented by Euratom), India, Japan, the Republic of Korea, the Russian Federation and the United States of America.

Cadarache, France was selected for the project construction in June 2005, a Director-General was chosen in November 2005, and Negotiations on the Joint Implementation Agreement (JIA) for ITER Construction, Operation and Decommissioning were completed at the end of 2005. The seven Parties initialled the JIA on May 24th 2006. It is expected to be signed in late 2006 and ratified where necessary by national governments as soon as possible thereafter. It should therefore be possible for the ITER Organisation to be constituted and start work at the beginning of 2007. In parallel, the framework of the new organisation is being established and located in Cadarache.

The current focus of work in this team is on finalising the safety report necessary to describe the device and its performance for the licensing authorities. This is envisaged to be submitted by late 2007 at the latest, in order to receive the license after public enquiry before the end of 2008. The long lead item technical specifications are being written in discussion with the future Domestic Agencies wherever possible. The Domestic Agencies are expected to be in position to launch the first calls for tender at the beginning of 2007. Quality, risk management, document management, planning and financial management systems are being introduced, and the project control infrastructure for a complex distributed-manufacturing international project is being put in place.

2. Why fusion energy?

When the nuclei of two light atoms fuse to form a heavier one, a large amount of energy is released. This is the process that generates the energy of the sun and stars. Fusion energy development, of which ITER is the key step, aims to harness the most reactive fusion reaction. That occurs between two isotopes of hydrogen, deuterium (D) and tritium (T), and the aim is to use the binding energy of the strong nuclear force released in each reaction to provide a sustainable solution to global energy needs. Each reaction produces a neutron and an inert helium nucleus, which carry the released energy as kinetic energy. The neutrons slowing down in materials surrounding the reaction chamber then allow the generation of electricity from the heat produced, and the charged helium nucleus slowing down in the plasma helps to maintain the reaction temperature.

The potential energy density of the fuels is very high. For example the amount of deuterium in 45 litres of water and the amount of lithium (used to breed tritium using the reaction product neutron) in one laptop computer battery provides enough energy for 30 years electricity use for someone in a developed country. The fuels are widely available. Deuterium is present at about 33 g/m$^3$ of water. The widespread land-based lithium reserves (lithium is the twenty-second most common element in the earth’s crust) are enough for thousands of years of baseload power generation worldwide, and if the
lithium in sea water is counted too (lithium salts are a by-product of desalination) the fuel reserves stretch to millennia.

There are two main approaches to making a fusion power station, based on magnetically confining DT plasma or by micro-explosions of inertially heated DT pellets. For success, the latter requires the development of very efficient lasers, and current experiments are a long way from approaching what is needed for net plant electricity production. Magnetic confinement, however, with ITER, is at the stage of being able in principle to generate enough energy, if it were to be converted to electricity, to provide for all internal power consumption. In other words, it is at the stage of a zero power reactor, and the machine to follow ITER, DEMO, can already be foreseen as a net producer of electricity for the consumer.

3. What is ITER?

ITER (“the way” in Latin) is the essential next step in the development of magnetic confinement fusion. Its strategic objective is to demonstrate the scientific and technological feasibility of fusion power. ITER will be the world’s biggest fusion energy research project, and an international collaboration. It is to be built in Europe, in Cadarache (France).

ITER is the most expensive and extensive scientific cooperation after the International Space Station. Over half the world’s population are now involved in the project through their government’s participation. ITER is the bridge between the scientific investigation of fusion and its exploitation and technological implementation.

Among other things, ITER will
- demonstrate up to steady state fusion power production - the tokamak confinement which ITER uses is basically restricted to pulses of 6 minutes but this can be extended by judicious use of plasma heating systems to drive plasma current, and steady state conditions have already been produced experimentally, but have to be demonstrated also in ITER;
- have a plasma which produces at least 10x more power than needed to run it - an essential ingredient for net electricity generation in a future plant is that the prime mover generate a sufficient excess of power to cover internal plant consumption, leaving something over for commercial consumption;
- study and optimise plasma behaviour - although there have been more than 40 years of increasingly successful research on Tokamaks, much remains to be understood about the fundamental processes at work and their interaction, and ITER’s plasma will be the first opportunity to study these at a scale predicted to be appropriate for power generation, so there are bound to be lessons learnt about how best to exploit practically the power of fusion;
- have dimensions comparable to a power station - not only the plasma, but all the major components are similar in size to those predicted to be needed for power generation, and in some cases have similar or greater performance requirements, and this already is a good test of industry’s capabilities to manufacture the necessary quality components at commercial scale;
- produce about 500 MW of fusion power, a power level comparable to a small power station, and indicative of the necessary scaleup to commercial power reactor size (about a factor of 6 in fusion power), and expected to be about 30% in linear dimensions of the tokamak (see later);
- demonstrate or develop all the new technologies required for fusion power stations - superconducting magnets to minimise plant internal power consumption, remote handling to replace radiation-damaged components, high heat tolerant components to act as the first material interface with the plasma, and high temperature tritium-breeding blankets to provide turbine-efficient coolants and to breed sufficient tritium to sustain the fusion reactions - low activation structural materials suitable for DEMO are not qualified for use on ITER, and their endurance under radiation damage cannot adequately be tested on ITER, as it would be too slow and costly;
- require about 10 years for licensing and construction based on a realistic but success-orientated schedule for the assembly process, and relying on the ITER procuring parties working together seamlessly - this schedule is now under review involving also risk assessment and minimisation;
• operate for about 20 years - initial operation, like nearly all plasma physics experimentation world-wide to date, will take place in pure hydrogen so as not to make the vessel internal components and systems radioactive, thereby enabling any early problems to be more easily and quickly solved; after about 4 years operation will increasingly involve deuterium and tritium, making the machine internals radioactive and requiring remote maintenance; the initial focus will be on plasma physics optimisation and stretching of the pulse towards steady state operation, followed later by repetitive long pulses to determine the most attractive tritium-breeding blanket for DEMO
• cost about €5bn to construct (over about 10 years) and €5bn to operate (about 20 years) - this cost is estimated based on an evaluation by the industry of Europe, Russia and Japan (the ITER Parties in 2001) of these costs in detail, based on materials and manufacturing time estimates, and worldwide material costs; this valuation was used by all the Parties in the negotiations as the basis for procurement sharing, but it is then up to the Parties concerned to provide their share of procurement, whatever the actual cost to them; the construction costs include construction team costs of about 16%, and the operation costs include a yearly levy, accumulating to cover decommissioning costs of about €500M.

4. ITER History

ITER has been a world-wide collaboration between the major countries investigating fusion since 1988. It was started following a proposal by Michael Gorbachov to Ronald Reagan at the Geneva Superpower Summit in 1985, to set up an international project to try to develop fusion energy. The initial ITER Parties were the Soviet Union, USA, Japan, and Europe (represented by the European Atomic Energy Community, Euratom). The conceptual design was completed in 1991. After lengthy discussions on where to site the design team, engineering design activities were split over three Joint Work Sites, in Japan, Germany and California, which worked together on what turned out to be considered an ambitious design aiming at plasma ignition (i.e. no need for external plasma heating to keep the plasma hot) until 1998, backed by R&D on key components carried out by the Parties.

While agreeing that the resulting design satisfied the objectives set, the Parties in 1998 could not agree on construction nor countenance the cost. The USA left the project in 1999, and the remaining three Parties set about designing a slightly less ambitious machine, aiming at high power amplification (> 10x more fusion power out of the plasma than needed to keep it hot) at about half the cost, but still allowing the development programme of one device between existing experiments and the electricity-generating DEMO. The detailed engineering design of this machine [1] was completed in 2001, and negotiations on where and how to construct ITER began. Four sites were proposed: in Canada, Japan, Spain and France, and after 4 years of discussions a site was finally agreed in Cadarache, South of France, in mid-2005. Meanwhile the People’s Republic of China had asked to become involved in negotiations on the construction in January 2003, and the USA had exercised its open option to rejoin. The Republic of Korea joined negotiations in mid 2003, and India became a full participant at the end of 2005.

5. Construction Schedule
The current construction schedule of ITER is shown in Figure 1. This schedule was derived in 2001, on the basis of details of the design then, on just three Parties participating, and without sharing within procurements. A review of the schedule taking account of split procurements and seven Parties, scheduled for 2007, may reveal that changes are necessary. The fact that there are more Parties can be beneficial in that there is more cover if a manufacturing process fails to reach the necessary quality level. On the other hand the coordination of actions in more Parties runs the risk of logistical failures accumulating schedule delays, and which effect dominates remains to be seen. The current schedule foresees first plasma by the end of 2016. Critical items are the buildings and assembly process, magnet and vacuum vessel manufacture, and commissioning.

6. **Key steps to implementing fusion power**

Neutrons produced in ITER, when not being captured in lithium for tritium breeding, activate surrounding materials. Due to the material damage caused, these have to be replaced every few years, and along with plant decommissioning, this creates some radioactive waste. To exploit the main advantages of fusion therefore, it is essential to develop also durable low activation materials.

Materials R&D shows that isotopic tailoring of existing materials - martensitic or ferritic steels, silicon carbide, or vanadium alloys - allows material re-use after ~100-300 years. Although these materials look promising at laboratory scale, the extent to which the commercial product maintains the properties needed, remains to be demonstrated to nuclear licensing authorities. Reactor scoping studies [2] show recycling could be carried out on all materials after 100 years, but some recycling after 100 years on some design options is “remote-handling-assisted” as it is still too hot for prolonged personnel exposure due to its iron content. For silicon carbide structures, full hands-on recycling after 100 years is achievable.

To test and qualify such materials for DEMO, an International Fusion Materials Irradiation Facility (IFMIF) is planned to operate in parallel with ITER. Building on the results, a demonstration fusion power station (DEMO) can then be designed, whose construction will open the way to the commercial exploitation of fusion.

The development schedule for fusion power therefore is envisaged as shown in Figure 2. ITER and IFMIF operate in parallel and feed information to DEMO, and under a “fast track” assumption DEMO is prototypical of a commercial power station, allowing commercial-sized plant to be constructed from
about 2050. The tokamak is presently not the only magnetic confinement scheme being studied worldwide. Also the stellarator or spherical tokamak are promising candidates, although they are less well developed to date. If by the time it comes to building DEMO these confinement schemes look more promising (the stellarator is for instance inherently steady state), then the technical work of ITER would not be wasted - it is equally applicable to these confinement schemes.

![Development Schedule of Magnetic Confinement Fusion](image)

### 7. Main scientific and engineering challenges

The main scientific and engineering challenges of ITER are reliability and performance. A fusion power station is a complex of many interacting systems:

- high current high energy superconducting magnets;
- high temperature and cryogenic components in close proximity;
- rapid remote replacement and refurbishment of damaged irradiated components;
- tritium cycle and breeding.

A key issue is whether these systems can be brought together to operate sufficiently reliably to make an efficient electrical power source without excessive need for redundant components and systems. To check the feasibility of ITER component design, a considerable R&D programme was carried out mainly between 1992 and 1998. This $600M programme focussed mainly on prototypes of the main machine components - vacuum vessel, divertor, blanket and magnets, and the remote maintenance of in-vessel components. These projects were all multiparty, and established the principles of working together on common projects and obeying common standards of manufacture. The results were highly successful. Magnet model coils were produced which mimicked ITER conditions, and these broke all superconducting coil performance records. A vacuum vessel sector was made with ±3mm tolerance, plasma-facing components of the divertor demonstrated the heat resistant performance and fatigue lifetime required for ITER use, and blanket first wall manufacture demonstrated that a number of options were available for reliable plasma-facing material joints, and that the blanket attachment scheme would work. The procedures necessary to replace and refurbish blanket and divertor components were rehearsed, leading to justification of acceptable machine refurbishment times. This verification process forms the basis of confidence in being able to construct and operate ITER successfully.
How confident can one be about ITER performance and that of the power reactors beyond? Figure 3 shows that up to the late 1990s progress was steady and better even than the leading high technology developments. Predictions of performance for ITER based on current experiments give considerable confidence that it will achieve its objectives and beyond. But fusion performance has essentially not advanced since 2000, and now needs new experiments to confirm the best way forward. Looking beyond ITER, studies [2] show that a power plant needs to produce about 6x more fusion power. Given the cost of ITER, which though high, is in many respects indicative of the components needed in a power plant, such an increase needs to be achievable with a relatively small increase in device and plasma size, typically 30-50%, or the plant economics would be threatened.

8. Features of ITER construction

ITER construction has unique features in an international science project. Procurement falls into three categories (see Figure 4): in-kind sharing of high technology components and systems, those (e.g. buildings) suitable out for the host, and cash fund. The in-kind contribution and provision by the host in ITER is 90% of the project value, and the funds for these procurements are controlled by the ITER Parties’ “Domestic Agencies”, not the project. Nevertheless, the project is responsible for writing the technical specifications for procurements and for monitoring the quality of the manufactured product. The success of ITER procurement therefore depends on the project team working well with the Domestic Agencies staff to correct quality problems or implement design changes. It will do this through Field Centre managers who will call in expertise from the central project team as needed when problems arise.

Procurement sharing is shown in Figure 5. Tokamak procurements, diagnostics and heating systems, are shared by all Parties, whereas buildings, and specific conventional plant, are covered by just one or two.
Because of its relevance for future fusion power plant construction, each ITER Party is very interested in developing industrial knowhow in key technological areas - in particular superconducting magnets and high heat flux components. However with seven Parties involved, procurement of these components becomes a difficult quality control problem, which may not be the cheapest or least risky solution. Splitting key procurements between many Parties introduces coordination problems: timing of delivery, uniformity, conformance to a common familiar standard, and management of the different supply chains. But the multiplicity of suppliers provides backup for failure, and increases future competitiveness.

9. Conclusions

ITER is the key step that will show whether magnetic confinement fusion can make a viable energy source. It will produce key data to optimise reactor performance, demonstrate all key technologies for power generation except materials endurance, and show how to design a demonstration/prototype electrical power source. The international legal framework is agreed, and over half the world’s population represented. A new organisation under international law is being established. The design is well established, a site is chosen and team-building is underway. It is a challenge - multiparty, shared procurement, complex, technically challenging, but it is a model for other international cooperations.

References


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