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ITER on the road to fusion energy

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Abstract
On 21 November 2006, the government representatives of China, the European Union, India, Japan, Korea, Russia and the United States firmly committed to building the International Thermonuclear Experimental Reactor (ITER) [1] by signing the ITER Agreement. The ITER Organization, which was formally established on 24 October 2007 after ratification of the ITER Agreement in each Member country, is the outcome of a two-decade-long collaborative effort aimed at demonstrating the scientific and technical feasibility of fusion energy.

Each ITER partner has established a Domestic Agency (DA) for the construction of ITER, and the ITER Organization, based in Cadarache, in Southern France, is growing at a steady pace. The total number of staff reached 398 people from more than 20 nations by the end of September 2009. ITER will be built largely (90%) through in-kind contribution by the seven Members. On site, the levelling of the 40 ha platform has been completed. The roadworks necessary for delivering the ITER components from Fos harbour, close to Marseille, to the site are in the final stage of completion. With the aim of obtaining First Plasma in 2018, a new reference schedule has been developed by the ITER Organization and the DAs. Rapid attainment of the ITER goals is critical to accelerate fusion development—a crucial issue today in a world of increasing competition for scarce resources.

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1. Introduction

Harnessing the energy of thermonuclear fusion reactions is one of the greatest challenges of our time. Fusion, the nuclear reaction which powers the sun and stars, would provide mankind with a safe, environmentally responsible and almost limitless source of energy. Fusion energy is a critical issue today because it has the potential to generate enormous amounts of energy at low economic and environmental cost in a world of increasing competition for scarce resources.

In the 1930s, physicists unravelled the nuclear cycles by which stars produce prodigious amounts of energy for billions of years. Two decades later, most developed nations shared the ambition to create a comparable reaction in a man-made machine. For the past half-century, hundreds of experiments have explored the way to fusion energy. As early as the mid 1950s, '*fusion machines*' of various shapes, sizes and performance, such as pinch, mirror, stellarator or tokamak, have been operating in the Soviet Union, the US, the UK, Germany, France and Japan. However, the way to fusion power has proved to be more difficult, complex and costly than first anticipated.

By the late 1970s, it had become obvious that no nation, whatever its resources, could by itself address the magnitude of the task. Three large tokamak projects in the EU, US and Japan were started in this decade. At about the same time, the US, USSR, Japan and Europe were engaged in an international effort to develop an even larger experimental fusion reactor—INTOR, the International Tokamak Reactor.

This paper reviews the history and presents the status of the ITER programme. It covers the staff build-up, the Organization structure, the licensing process, the present state of the works on the ITER site and the ITER itinerary, and shows how ITER, one of the most innovative and challenging scientific projects in the world today, is also a prototype for large scale international collaboration in science and technology.

2. History of tokamak devices

In the past 50 years, considerable advances have been made towards the achievement of controlled thermonuclear fusion. Progress in temperature and plasma confinement time has been as steady and as spectacular as the growth in the performance of microprocessors—indeed slightly better (figure 1).

Tokamaks, which were developed in the late 1950s, first in the Soviet Union, then in the US, Europe and Japan, and more recently in China, Korea and India, have also dramatically increased in size. In 1957 the Soviet T-1 had a plasma volume in the range 0.4 m^3, JET's was close to 100 m^3 and ITER's will be close to 900 m^3 (figure 2).

The rapid growth in tokamak research was launched by the remarkable results reported from the T-3 tokamak at the Kurchatov Institute in Moscow by a British–Soviet

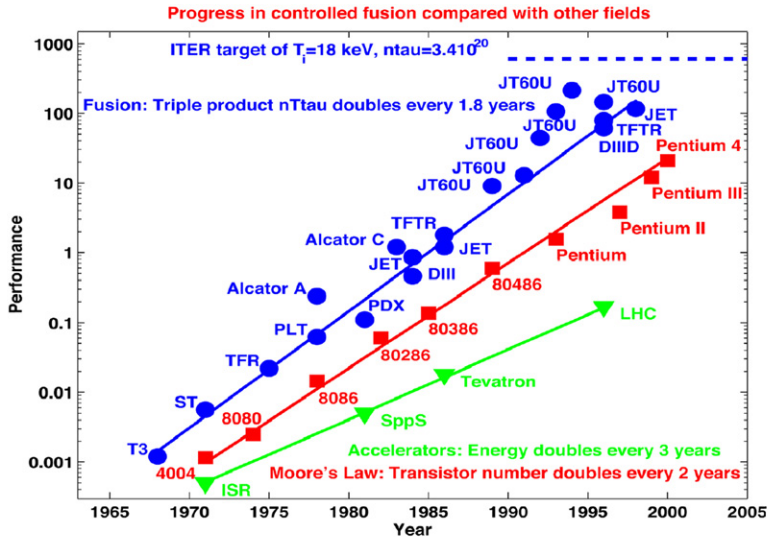

Figure 1. Since the mid 1970s, following 'Moore's law', the number of transistors in a microprocessor has doubled every two years. In the same period, the 'triple product' of density, temperature and confinement time, which measures the performance of a fusion plasma, has doubled every 1.8 years.

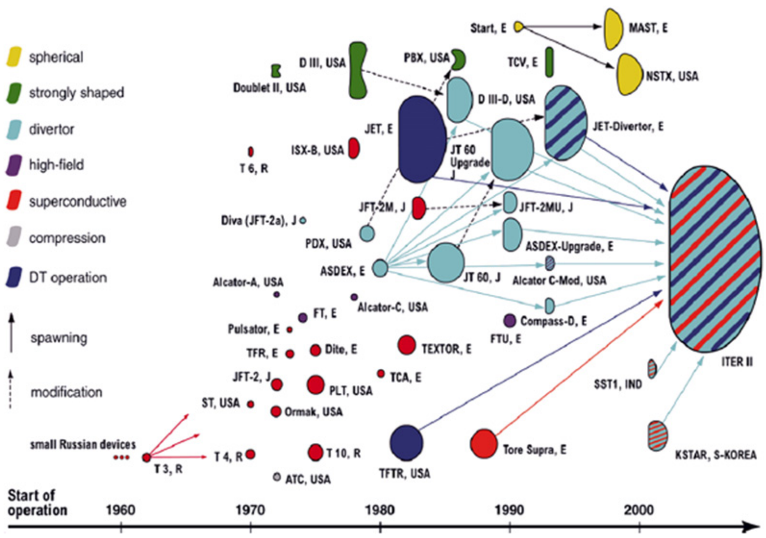

Figure 2. Overview of the development of tokamaks during the past 50 years in terms of their size, poloidal shape, power and particle exhaust concept, magnet technology and mode of plasma operation.

collaboration [2]. Using Thomson scattering to measure the electron temperature, the group reported observations of electron temperatures approaching 1 keV. Many of the world's leading fusion research laboratories turned their attention to tokamaks as a result, and the gradual increase in size and additional heating led to gradually improving plasma parameters, exemplified by the achievement in neutral beam heated discharges of ion temperatures of 7 keV in the PLT tokamak in Princeton in 1978 [3].

While tokamaks with predominantly circular cross-sections were making the headlines experimentally during the 1970s, two new generations of devices were not only on the drawing board, but were under construction. The first generation was not much different in size from the largest of the 1970s devices, but had an increased level of sophistication, including features such as a poloidal divertor. Soon after one of the first of these devices, the ASDEX tokamak in Garching, commenced operation, one of the most fundamental discoveries in fusion research was announced: operating in a 'diverted' configuration with neutral beam injection heating, the ASDEX group reported [4] in 1982 that an unexpected transition in the plasma confinement properties had occurred, approximately doubling the plasma energy confinement time. In the course of the 1980s, much tokamak research time was devoted to exploiting and understanding this new 'H-mode' operating regime.

The second generation of new devices consisted of the group of large tokamaks, TFTR in Princeton, JET in Culham, JT-60U in Naka and T-15 in Moscow. It was this generation of devices that led the way towards the brink of DT fusion power production in the 1980s, a promise

Figure 3. When President Reagan and Secretary Gorbatchev met for the first time in Geneva in November 1985 fusion was on their agenda.

which would be fulfilled in the 1990s. JET made the transition to operation with deuterium–tritium fuel mixtures first, with initial DT fusion experiments in 1991 [5], and subsequent experiments achieving a peak fusion power of 16 MW [6] by exploiting the H-mode discovery of ASDEX. TFTR undertook a wide-ranging experimental programme on DT plasmas [7] and achieved a peak fusion power production of 11 MW. Although JT-60U did not operate with DT fuel, it carried out extensive exploration of plasmas with high fusion performance and achieved the record 'fusion triple product' value of $n_i(0)T_i(0)\tau_E = 1.5 \times 10^{21}$ keV s m^{-3} in 1996 [8] (see figure 1).

Smaller tokamaks and stellarator devices using superconducting magnets to confine the plasma have operated in a stable manner for long periods—5 h in the case of the Japanese tokamak TRIAM 1 [9]—thus opening the way for continuous operation in a future industrial reactor.

Although JET and TFTR have produced significant amounts of fusion power, this was less than the power consumed to heat the plasmas initially. A larger experiment was therefore necessary to achieve a fusion power output significantly greater than the power input.

This is the aim of ITER, whose dimensions were defined by scaling laws derived from data collected worldwide: to achieve a power amplification (Q) of 10 and to demonstrate that fusion energy is a viable option for producing electricity on an industrial scale.

3. History of the ITER project

These tokamak projects, in the US, the Soviet Union, Japan and Europe, were making significant progress when in November 1985 US President Ronald Reagan and Soviet Secretary General Gorbatchev met for the first time in Geneva (figure 3).

Fusion energy was one of the items on their agenda. Both leaders agreed to '*the widest practicable development of international cooperation*' in developing fusion research with the aim of '*obtaining this source of energy (. . .) for the benefit of all mankind.*' Two years later, at the Reykjavik Summit, an agreement was reached for the EU and Japan to join the project and pursue the design for a large international fusion facility—the International Thermonuclear Experimental Reactor (ITER) into which the INTOR project was eventually folded.

Translating the Geneva and Reykjavik commitments into reality was to take two decades, during which the world of fusion science was to implement an international cooperation of a unique kind and scope. In ITER, every one of the Members involved was strictly equal to the others and every decision was reached through consensus.

The ITER project actually began with Conceptual Design Activities (CDA) in April 1988. Under the auspices of the International Atomic Energy Agency (IAEA), the CDA took place in Garching, hosted by the Max-Planck-Institut für Plasmaphysik (IPP). Some 50 professionals worked together for about six months each year to define the conceptual design of ITER. The work was carried out jointly by all the Members, in order to be sure of building consensus (see, e.g., [10, 11]).

Success in CDA led to preparations for an engineering design phase. The Engineering Design Activities (EDA) started in 1992 at the three joint worksites in the EU, Japan and the US. The ITER design developed during this major design and R&D programme evolved through several stages [12, 13] before culminating in the design [1, 14] which provides the basis for the ITER facility now under construction at Cadarache. The product of these activities was a complete and fully integrated documentation of a new ITER design produced to a level suitable for the Members to make a decision on construction, including a full cost analysis and a safety assessment for ITER located at a 'generic site'. The Final Design Report [1] was approved by the ITER Council in July 2001.

During the ITER EDA, key prototypical high-technology equipment, such as superconducting coils, remote handling systems and high heat tolerant components, were developed specifically and manufactured by the industry through ITER R&D programmes.

After completion of the ITER EDA, Canada proposed an ITER construction site in Clarington, a suburb of Toronto, and the governmental negotiations on the drafting of the ITER Agreement started in late 2001. By autumn 2002, four candidate sites had been formally proposed and joint

Figure 4. On 21 November 2006, governments of the ITER Members signed the ITER Agreement.

assessment of the proposed sites began. In June 2005, the construction site was unanimously agreed upon in Cadarache, France, and the nominee Director-General (DG) of ITER was chosen. It was decided that ITER would be built in Cadarache, adjacent to the largest French research centre Commissariat à l'Énergie Atomique (CEA).

On 21 November 2006, at the Élysée Presidential Palace, in Paris, the governments of China, the EU, India, Japan, Korea, the Russian Federation and the US signed the ITER Agreement (figure 4).

The ITER Agreement entered into force and the ITER Organization was formally established on 24 October 2007 after ratification. France and the ITER Organization signed the Headquarters Agreement on 7 November and three weeks later, on 27 November, the first official ITER Council meeting was held at Cadarache.

4. Growth of the ITER Project Team

4.1. ITER Domestic Agencies are building their capabilities

A unique feature of ITER is that almost all of the plant components will be provided to the ITER Organization through in-kind contributions from the seven Members—China, the EU, India, Japan, Korea, Russia and the US. In this perspective, each Member has set up a DA, installed on its own territory, which employs its own staff and is responsible for the procurements of its in-kind components.

While the ITER Organization is responsible for the overall design, integration, civil construction, installation and commissioning, the staff in the DAs will execute detailed design, procurement, vendor oversight, testing and delivery. Defining the roles and responsibilities of the DAs and the ITER Organization as the project moves forward towards industrialization will be crucially important.

4.2. Staffing the ITER International Organization

ITER is now securely on track. The original team, of just seven people, was on the CEA premises in Cadarache at the end of 2005 (figure 5). By early 2008, the ITER team comprised of 219 staff members from 22 nations plus subcontractors and visiting scientists.

Figure 5. The original ITER team in December 2005

By the end of September 2009 the ITER Organization employed a total of 398 staff including 278 professional staff and 120 support staff (figure 6). By the end of 2009, some 450 persons will be working full time for the ITER Organization.

The present distribution of the professional staff is as follows: 59% European, 8% Japanese, 8% Russian, 5% Chinese, 7% Korean, 8% American and 5% Indian (figure 7). About a third of them have moved into the recently completed temporary Headquarters building, next to the ITER work site. The ITER Organization will be hosted in a new permanent office building in a few years.

The architectural drawings for this permanent building are complete and the calls for tender for the construction were launched in 2009, with construction expected to start by the end of the year (figure 8).

The ITER Organization is still in the middle of recruitment and build-up. Total staff numbers should reach 700 when the machine starts operations less than ten years from now. The primary consideration in the recruitment and employment of staff is to recruit employees of the highest standards of efficiency, technical competence and integrity. The ITER Organization is a multinational environment, and prospective staff must be able to cope with cultural differences and various approaches to problem solving and decision making.

ITER Group Picture on 27 May 2009

Figure 6. By the end of 2009, some 450 persons will be working full time for the ITER Organization.

	Professional	Support	Total
CN	15	0	15
EU	164	98	262
IN	14	9	23
JA	22	5	27
KO	19	1	20
RU	21	2	23
US	23	5	28
Total	278	120	398

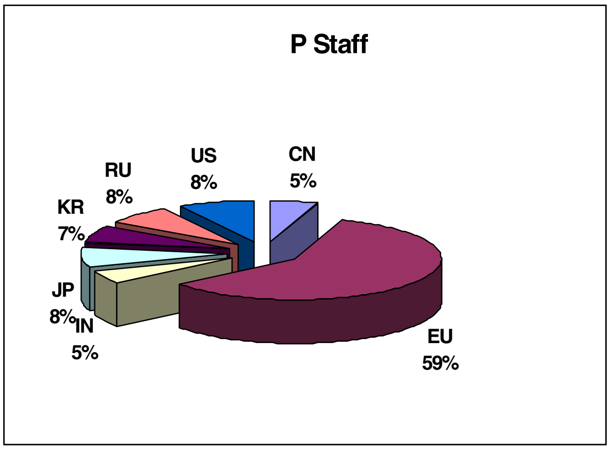

Figure 7. Distribution of the ITER professional staff.

The selection process for candidates is carried out with the support of the Members. After nomination of qualified candidates for the open positions through the Members, the ITER Organization evaluates the applicants' qualifications and carries out interviews in order to make the final selection. Only people from the ITER Members can apply to a position within the Organization.

4.3. The ITER International Organization: Structure and Senior Management

The ITER Organization Structure and Senior Management are shown in figure 9. The ITER Council is the governing body of ITER. It is composed of representatives from the seven ITER Members and meets at least twice a year at the Headquarters of the Organization unless decided otherwise. The ITER Council has the power to carry out several functions, including appointing senior staff, amending regulations, deciding on budgets and allowing additional states or organizations to participate in ITER.

The Council is supported by

- the Science and Technology Advisory Committee (STAC) whose role is to advise the Council on science and technology issues that arise during the course of ITER construction and operation;
- the Management Advisory Committee (MAC) which advises the Council on strategic management issues during the development of the ITER project;
- a Financial Audit Board, consisting of seven independent auditors from the seven ITER Members, which examines whether the financial statements, including balance sheets, expenditure tables and contracts, are in line with the Project Resource Management Regulations.

The Chief Executive Officer of the ITER Organization is the Director-General, who is appointed for a five-year mandate which can be extended once.

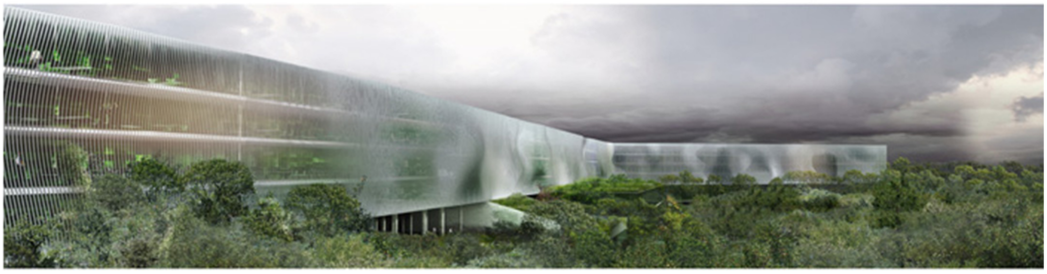

Figure 8. The future ITER Office building.

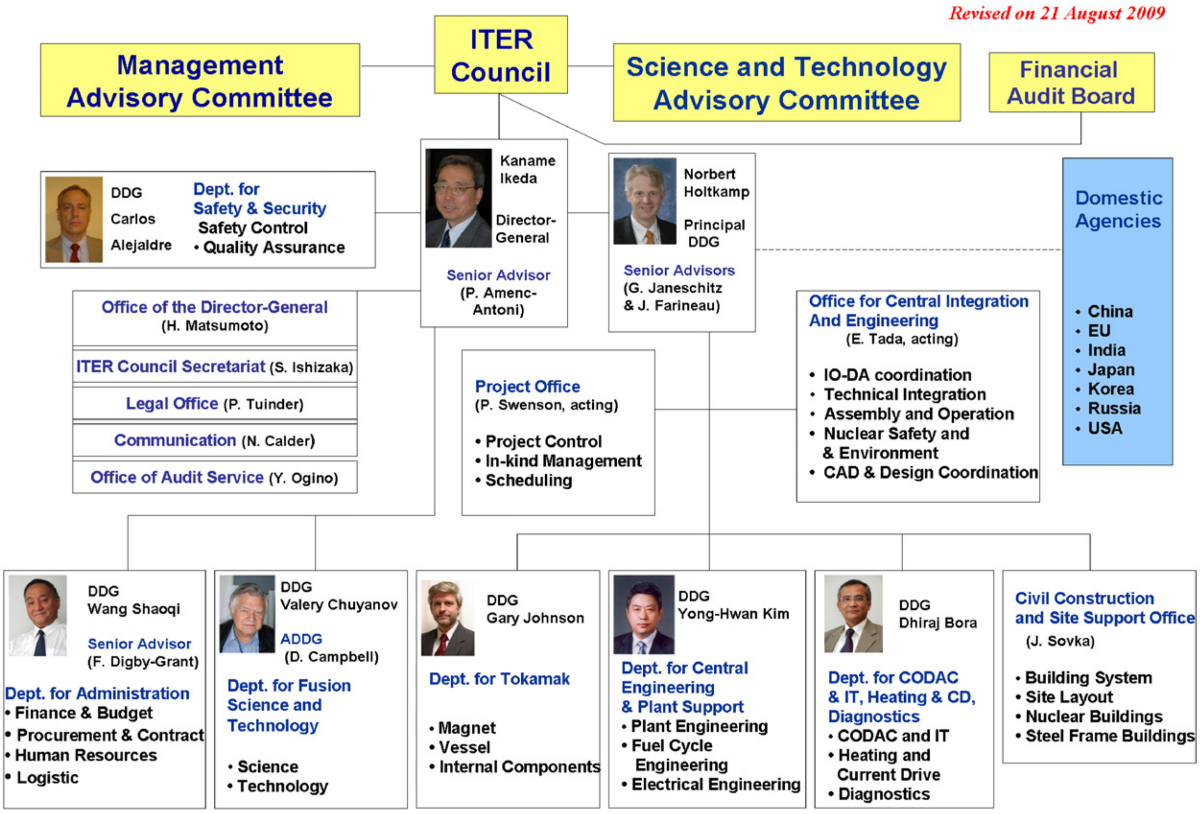

Figure 9. The ITER Organization Structure and Senior Management.

The Director-General represents the ITER Organization, and is responsible for

- the safety and observance of the law, licensing and quality assurance;
- drawing up budgets and monitoring expenditure of the Organization, as well as the project schedule;
- organizing the ITER Council meetings and supplying necessary information for its subsidiary committees on management and science.

The Director-General is assisted by a Principal Deputy Director-General and Project Construction Leader (PDDG), and by six Deputy Director-Generals (DDGs), each responsible for a Department and chosen to achieve a balance between the Members. The ITER Organization Departments and Offices are as follows:

- Department of Safety and Security
- Department of Administration
- Department of Fusion Science and Technology
- Department of Tokamak
- Department of Central Engineering and Plant Support
- Department of CODAC and IT, Heating and CD, Diagnostics
- Project Office
- Office for Central Integration and Engineering
- Civil Construction and Site Support Office
- Office of the Director-General

5. Licensing process

ITER will be an 'Installation nucléaire de base' and, as such, will comply with French regulations and procedures. On 31 January 2008, the files for the '*Demande d'Autorisation de Création*', including the Preliminary Safety Report, in application of the Nuclear Safety and Transparency law (TSN), were sent to the French Nuclear Authorities. Examination of

Figure 10. The levelling of the 40 ha ITER platform is now complete.

the files is ongoing and a Public Enquiry is foreseen upon its completion. The issuance of '*Décret d'Autorisation de Création*' could be expected after the formal examination by the *Groupe Permanent*. The following step in the licensing procedure to start operation with radioactive fuel is the '*Autorisation de Mise en Service*' which has to be obtained within the deadline fixed in the '*Décret d'Autorisation de Création*'.

6. Construction site

Agence ITER-France (a CEA agency established by France under the terms of the Site Support Agreement) is responsible for earth moving and site levelling. Preparatory work on the ITER site started at the beginning of 2007 and the levelling of the 40 ha platform is now complete. Almost 2.3 million m^3 of material have been cleared in the process, among which 1.1 million m^3 have been re-used on site (figure 10).

In addition, excellent progress has been made in completing the many kilometres of access roads, drainage pipes, retention basins and other infrastructure required to support the construction of the ITER facility. Excavation works for the tokamak building are expected to begin in 2010. The European Domestic Agency, Fusion for Energy (F4E), based in Barcelona, will allocate more than 150 people to the ITER site in order to oversee this effort, and to carry out the detailed design of all ITER buildings.

7. ITER itinerary

Components for the machine, some of them very large, will be manufactured by the Members in facilities located on their territory and will have to be delivered to the ITER site (figure 11). The roadworks necessary for bringing the ITER components to the site from Fos-sur-Mer harbour, some one hundred kilometres south of Cadarache, started at the beginning of 2008 and will be completed by early 2010, when the first convoys are expected.

About 300 convoys will travel the ITER itinerary over the first five years of the construction phase, bypassing 16 villages and crossing two motorways. 16 roundabouts and 25 bridges have been modified to take the exceptional size and weight of the components into account, some of them with an individual weight, including the transport vehicle, of up to 900 tons and a total width of 9 m. Once loaded onto special flat-bed transporters, these components will travel by night at slow speeds in order to minimize disturbance.

Roadwork along the ITER itinerary is under the responsibility of France, whereas the transportation of components between Fos harbour and Cadarache will be financed by Europe.

8. ITER: a prototype for international collaboration in science and technology

ITER is one of the most innovative and challenging scientific projects in the world today. It is also a prototype for international collaboration in science and technology. The programme is pushing forward the frontiers of our knowledge and of our capacity to organize on a truly global scale.

Throughout the history of fusion research, and particularly since the 2nd Atoms for Peace Conference in Geneva in 1958, sharing information has enabled fusion scientists to learn from each other and fusion science to accomplish remarkable progress. While Euratom was established by the European Communities in 1957 to foster cooperation in the nuclear field, INTOR, in 1978, was the first truly international project in the field of fusion research and led thinking at the international level on the next step in magnetic fusion research through its several phases (see, e.g., [15, 16] . A collaborative venture between the US, the USSR, Euratom and Japan, INTOR has in several ways laid the blueprints for ITER, which, with

Figure 11. The roadworks of the ITER itinerary will be completed by early 2010.

strong political support from world leaders, was initiated in 1985.

ITER was fully internationalized from its inception, with a multinational Council governing the project, a multinational management, multinational advisory committees and international working groups. In ITER, scientists, engineers and administrators have demonstrated their ability to work together across national and cultural boundaries to accomplish a common goal.

8.1. International decision making

Sharing the construction cost and risk globally means learning to make decisions on a global scale. To make ITER a success in both construction and operation, it is essential that both the ITER Organization and the Members, through their DAs, share responsibility in an efficient and creative manner.

In this perspective, the ITER Organization has established structures, tools, communications procedures and integrated actions; and has created a global governance system that has no equivalent in the history of science.

Coordination meetings between the ITER Organization and the DAs (commonly known as IO–DA coordination meetings) frequently take place, as well as day-to-day bottom-up communication, both constituting essential tools for managing such a multinational endeavour.

8.2. Sharing the cost and the technology

Since ITER will be built largely (90%) through in-kind contribution by the seven Members, the ITER Organization is not directly involved in the management of the industrial contracts for in-kind procurement, but has the role of defining the procurement specifications (figure 12). It is also responsible for the whole integration process during the design and assembly phase. Sharing of the procurement scope was agreed taking into consideration the interest and capacity of each Member. Eventually, every Member will have acquired the knowledge that will enable it to design and build a prototype fusion power plant.

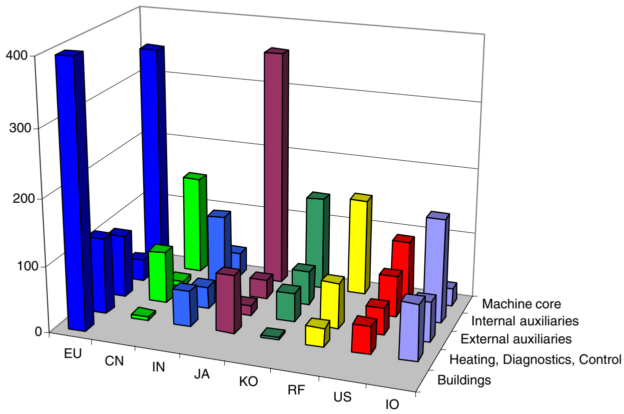

Figure 12. ITER will be built largely through in-kind contribution by the seven Members.

The design development has led to the definition of 92 Procurement Packages, each of which is allocated to more than one Member, leading to a total of about 200 Procurement Arrangements allocated to the ITER Members.

Although a number of Procurement Arrangements were signed in late 2007, procurement activities accelerated significantly throughout 2008. The main Procurement Arrangements which have been launched concern the poloidal field (PF) and toroidal field (TF) magnet conductors and the vacuum vessel.

9. Integrated project schedule

With the aim of obtaining First Plasma in 2018, a new reference schedule was developed by the ITER Organization and the DAs

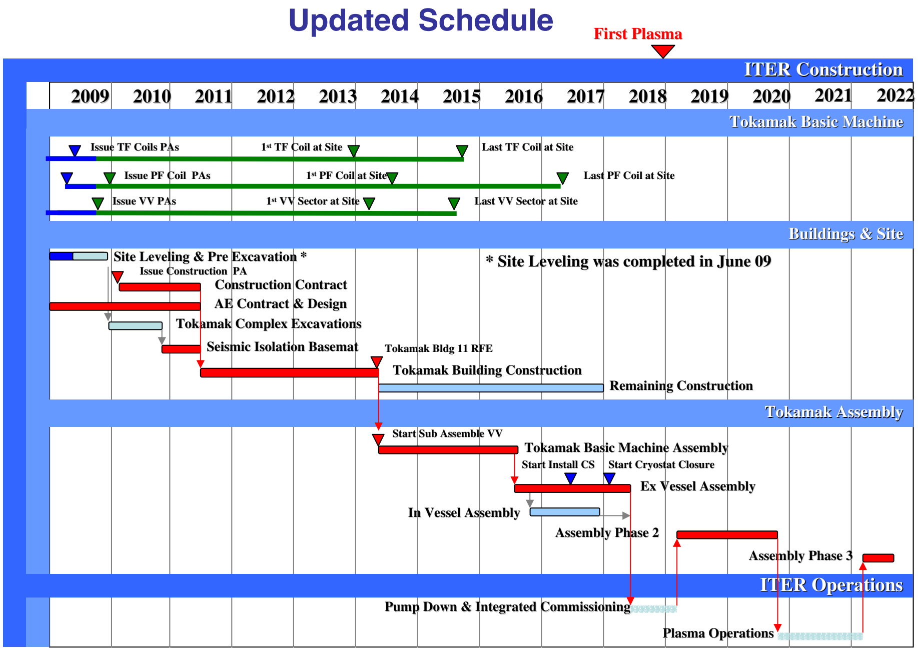

Figure 13. The updated ITER schedule.

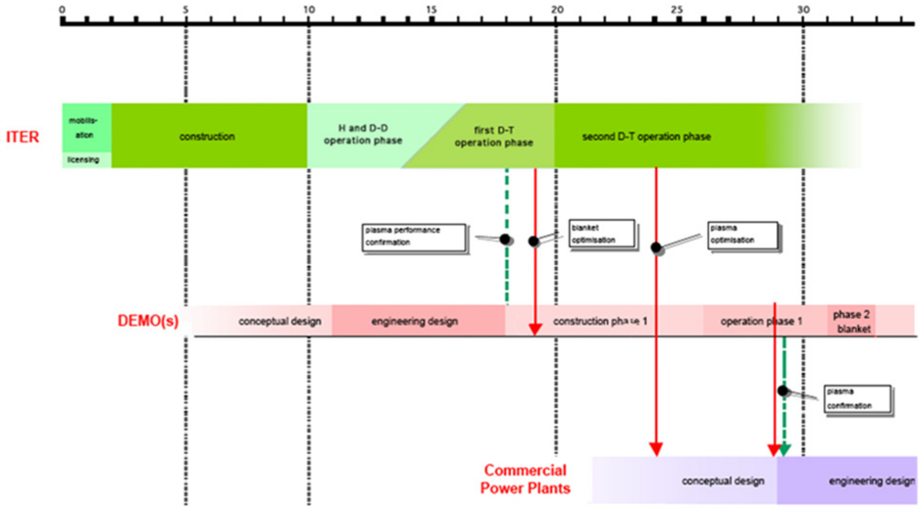

Figure 14. Respective timeline of ITER and the Prototype Power Plant DEMO.

(figure 13). The recent completion of site levelling will enable construction work to begin on various buildings. Tokamak complex excavation is scheduled to start in 2010 so that the building could be ready for equipment by 2014, when tokamak machine assembling will begin.

10. ITER is the critical step towards fusion energy

The rapid attainment of the ITER goals is critical to accelerate fusion development. While ITER is a decisive step on the path to industrial fusion energy, improving tokamak performance in other experiments remains essential, as is the intensification of R&D on materials for plasma facing and structural components.

Conceptual work for a Prototype Power Plant (‘DEMO’) could begin as early as five years from now while the ITER machine is being constructed. Figure 14 shows the respective timelines of both programmes, while figure 15 illustrates schematically the progression in scale and layout from JET to a possible DEMO device.

11. Conclusion

The ITER Organization is now well established and fully operational. Excavation works for the tokamak building are expected to begin in 2010 while the roadworks necessary for bringing the ITER components to the site will be completed by early 2010. The licensing process is ongoing and the main Procurement Arrangements have been initiated.

An integrated Project Schedule has been developed between the ITER Organization and DAs. Conceptual work

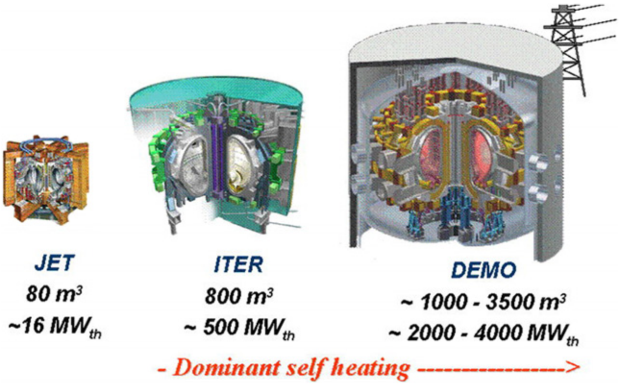

Figure 15. The growth in scale of tokamak devices from JET, which produced the first DT fusion power, through ITER, aiming for $Q = 10$ at 500 MW thermal, to a DEMO reactor producing ~1 GW electrical.

for a Prototype Power Plant ('DEMO') could begin in parallel with the construction of ITER.

What is being built in Southern France is a scientific experiment of an exceptional scale and ambition. ITER is an opportunity to make a crucial impact on the history of science and the future of our civilization. It is also a demonstration that nations, when confronted with a global challenge, can establish a completely new model for international collaboration.

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