Article 6: Politics and Progress

Commercializing fusion power will be an expensive and long-term undertaking, requiring progress at both national and international levels. Alternate ways of advancing the technology compete for limited budgets, and there is debate about the relative merits of national and international projects. This article reviews the history of political interest in magnetic confinement fusion and then discusses several key existing and planned fusion experiments.

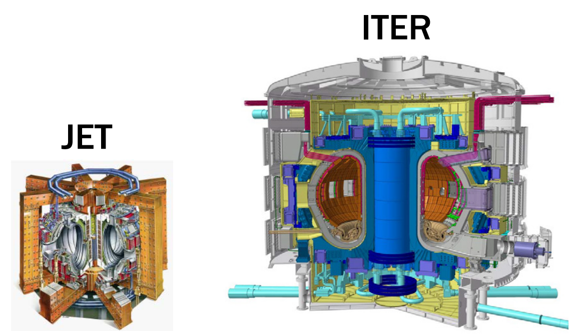
History of global cooperation

Fusion research has received decades of public funding in the U.S., Europe, and Russia; recently Japan, South Korea, and China have become significant contributors. The British, U.S., and Soviet governments conducted controlled fusion research efforts in secret laboratories in the years following World War II. Then, in the mid-1950's, secrecy gave way to openness. President Dwight D. Eisenhower's 1953 "Atoms for Peace" speech signaled increased political interest in peaceful uses of nuclear technology. By 1958, magnetic confinement fusion research was declassified in the U.S.

In 1971, the United Nations' International Atomic Energy Agency (IAEA) established the International Fusion Research Council (IFRC) to coordinate its response to proposals for experimental fusion reactors so large and costly that they required international collaboration. This forum was part of a broad effort to strengthen East-West ties through collaborative scientific ventures. In 1978 the Soviet Union proposed to the IAEA that an International Tokamak Reactor should be built, larger than any of the anticipated national reactors. At the time, the cost of this international collaboration was expected to exceed $1 billion *[1,2]*. The vision for an international research reactor has evolved over the decades into the International Thermonuclear Experimental Reactor, now known simply as ITER *[3]*. The collaboration currently has seven members: the European Union, China, India, Japan, South Korea, Russia, and the United States.

ITER, Latin: "the way"

ITER is the largest fusion research project in the world and is under construction in Cadarache, France, near the Rhone River -- with high-tech components that are being fabricated around the world. In Figure 6.1 the size and expected performance of ITER are compared with the achievements at the Joint European Torus (JET), currently the world's largest tokamak. The ITER facility seeks to produce 500 megawatts of fusion power with a D-T plasma with 50 megawatts of input power, a ten-fold return on energy input. The substantial fusion power of ITER is expected to be sustained for at least 400 seconds and to be repeated about once per hour. Achieving these performance parameters would allow the testing of a number of key issues that bridge the gap between small national experiments and projects addressing fusion at near-commercial scales. ITER is also expected to test plasma control, continuous fueling, tritium breeding, and other engineering issues associated with a commercial-scale reactor.



Plasma volume (cubic meter): 80
Fusion power (megawatt): 16
Pulse duration (second): 2

Plasma volume (cubic meter): 830
Fusion power (megawatt): 500
Pulse duration (second): 400

Figure 6.1: Expectations for ITER are compared with the achievements of the Joint European Torus (JET, at Culham, U.K.) *[4]*.

Delays have caused official milestone dates to slip repeatedly. ITER's design was approved in 2001, and a cooperative agreement was signed in 2006. Construction of ITER began in 2008. At the time of site selection in 2005, ITER was expected to be in operation by 2016 but this was moved back to 2018 and then 2019. At present ITER is expected to be operational in 2026. The estimated total cost of ITER initially ranged from $5 to $10 billion, then surpassed $15 billion and now exceeds $20 billion. Such estimates are difficult; in addition to engineering uncertainties, ITER members make most of their contributions through "in-kind" equipment.

Sustaining political investment in ITER

Rising estimates of ITER costs have caused members to reassess their commitment to the collaboration repeatedly *[5,6]*. Despite high-level interest in the long-term economic, environmental, and technological prospect of commercial fusion power, domestic decision-making is commonly shorter-term. Scientific prestige and economic stimulus have been important for the domestic political viability of ITER funding *[7]*, which in several countries consumes a substantial portion of the fusion budget. Sustained domestic political justification for ITER is buoyed by contracts for equipment awarded to domestic industry as well as complementary domestic fusion experiments.

The protracted conflict over which country would host ITER suggests that many countries expected that having ITER on their soil would nurture their domestic research programs in fusion and beyond. First came the search in the early 1990s for a single headquarters to coordinate engineering design for ITER; the result was three sites – in Germany, Japan, and the U.S.

Siting the reactor itself was even more contentious. In early negotiations, both France and Germany indicated they would not bid to host the ITER site, because the anticipated costs were too high. Spain meanwhile offered to double its contribution to ITER if its site was chosen. Japan's political commitment to ITER was volatile. In the late 1990s Japan, facing domestic cuts to public science expenditures, encouraged ITER to delay its schedule by several years so as to avoid being seen as a marginalized ITER partner *[8]*. Once its domestic budget shortfall was resolved, Japan offered to bear the entire costs of the reactor core if ITER was sited in Japan *[9]*. Eventually, France changed its position and came forward with a bid for building the project. Canada proposed a site as well – at Clarington, a suburb of Toronto. The U.S. and Russia considered making bids but refrained because of high costs.

The U.S. left the ITER collaboration in 1998 for three years as a result of budget concerns *[10]*. Five years later in January 2003, the U.S. re-entered ITER, reflecting renewed interest in Congress and diplomatic pressure from both Japan and Canada *[11]*. The U.S. rejoined just as China and South Korea became members and launched their own domestic fusion programs. Canada withdrew from ITER entirely in December 2003 after it became clear that it would lose its bid to host the project. The project picked up momentum nonetheless, with India joining ITER in 2005.

France was the favored location for the project within Europe (over sites in Germany, Spain, and Sweden) *[12]*. The European Commission then had to persuade the Japanese to abandon their bid to site ITER at Rokkasho. The high-level political stalemate between Japan (supported by the U.S. and South Korea) and France (supported by Russia, the European Union, and China) was technical, financial, and geopolitical *[13]*. After a year of negotiations, the European Union threatened to build the Cadarache reactor even without the support of the other ITER members. This threat forced supporters of the Japanese bid to consider the risk of the international enterprise splintering into multiple projects or falling apart entirely *[14]*.

Japan relinquished its bid in 2005 in exchange for sharing costs with the Europeans on a package of facilities located in Japan that would support both ITER and an envisioned successor international facility, called DEMO. The bargain included a supercomputing design center and a materials testing facility. Japan would also make an outsized contribution to ITER of in-kind equipment and project scientists, and ITER's first director general would be expected to come from Japan *[15]*. Figure 6.2 shows the ITER construction site in Cadarache, France as of February 2016.

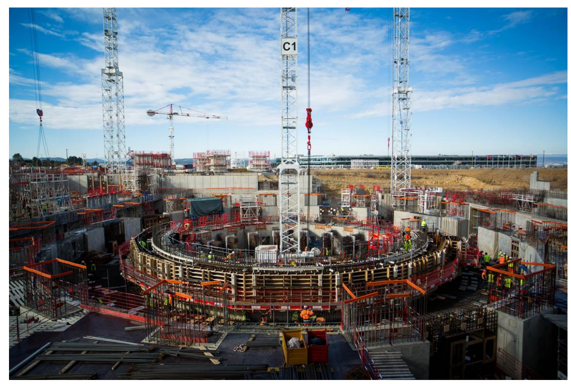


Figure 6.2: After years of delay and continued uncertainty in cost and timeline, ITER construction has begun. The circular structure is the beginning of the building that will house the tokamak. The photo is from February 2016 *[16]*.

Balancing domestic and international priorities

Exceptions for Japan aside, the burden-sharing agreement for ITER's "in-kind" sub-system contributions is quite straightforward: the European Union bears five elevenths (45.45 percent) of the overall project cost including all on-site buildings, and the other six partners contribute one eleventh (9.09 percent) each *[17]*. Before India's inclusion in ITER, the EU had taken on 50 percent and the other five members 10 percent each.

The objective of ensuring that investments in ITER serve domestic industrial and commercial interests has driven every stage of the ITER negotiations. To source equipment for ITER, the members crafted a cost-sharing agreement that divided the project into over one hundred "procurement packages" of in-kind equipment, summarized in Figure 6.3. Through these discrete contracts, countries individually maximize the present scientific and economic benefits of the project to justify their short-term costs and have less need to point to the long-term – and uncertain – payoff *[18]*.

With the help of Figures 2.1 and 3.1, we can elaborate on the distribution of effort shown in Figure 6.3. The EU is contributing a substantial share to all system categories, but particularly the buildings and machine core. It is also splitting the production of the toroidal field coils with Japan. Japan additionally is supplying the conductors for the central solenoid, and other elements of the machine core and control equipment. China has mainly been involved in the machine core (conductor cables for the magnets, main vessel, handling, and transfer systems) and external auxiliaries (electrical circuitry); India is the largest contributor to internal auxiliary systems and particularly the heating and cooling systems; South Korea contributes heavily to the vacuum vessel, heat shield and conductor cables; Russia provides poloidal coils, electronics, and parts of the chamber; and the U.S. contributes to exhaust, fueling and cooling equipment, central solenoid, and plasma heating and disruption mitigation technology – among other systems. The ITER Organization itself – using its operating budget from "in-cash" member contributions – also directly procures a significant portion of the auxiliary, cooling, and control systems.

ITER has had to contend with intellectual property rights, particularly each member's interest in keeping for itself any valuable information gained through participating in ITER. To minimize exclusive rights, ITER members in 2006 endorsed the "widest possible dissemination" of ITER intellectual property for most – but not all – technologies. They agreed that the sharing of background intellectual property and eventual experimental results should be on an "equal and non-discriminatory" basis among members *[21]*. The members have limited short-term commercial incentives because of fusion's multi-decadal development path *[22]*, and accordingly they generally see the synergistic value of ITER cooperation outweighing the benefits from exclusive rights to ITER-related inventions.

It is still possible that ITER will not be finished. Impatience with the continued delays in ITER's startup could imperil the participation of some countries in its construction or subsequent operation and lead them to return to national programs based on domestic experiments. The U.S. has threatened to exit ITER many times – most recently, during the June 2014 Senate budget discussions. However, according to the ITER agreement – which the U.S. has signed -- all of the in-kind contributions pledged by the U.S. would still be due in 2017. Even though the ITER organization has no means of enforcing member commitments, incentives to drop out become steadily weaker as construction proceeds.

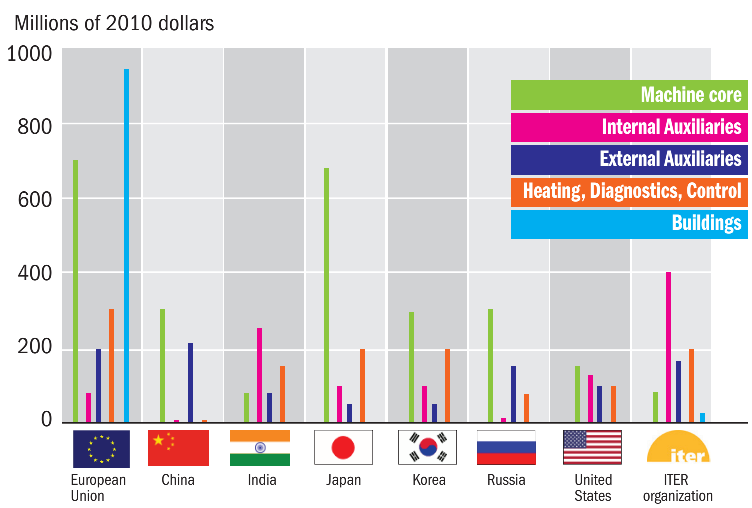


Figure 6.3: Value of the components and sub-systems contributed to ITER by its seven members and by the ITER Organization *[19]*. Ninety percent of each member's contribution is "in-kind" equipment (rather than direct payments) as part of over one hundred discrete procurement packages. The other ten percent of member contributions are made "in-cash" to fund the operational budget of the ITER Organization, which also directly procures some packages. Data are from early 2015. (The original data are in ITER Units of Account (IUAs), pegged to 2010 euros at 1552.24 euros = 1 IUA, which we have converted to 2010 dollars at US$1 = 1.33 euros) *[16,20]*.

Key domestic research programs

Alongside ITER are many single-nation research programs, ongoing and planned, whose objective is either to build up to ITER or to look beyond it. We briefly discuss several important experiments (three tokamaks and one stellarator), acknowledging that there are many others that make their own unique contributions to global fusion research.

Joint European Torus (JET): The Joint European Torus (JET) is to date the world's largest and most powerful operational magnetic confinement fusion device with the tokamak configuration. It is a European collaboration and was the first major international fusion project. JET is located at the Culham Centre for Fusion Energy in Oxfordshire, U.K. and has been operating since 1983 *[23]*. Unlike ITER, JET does not use superconducting magnets and is not suited for long-duration energy generation. Nonetheless, JET has set two world records: in 1991 it became the first device to produce one megawatt of power for two seconds using a D-T plasma with peak power of two megawatts *[24]*. In 1997, JET exceeded that record by producing 16.1 megawatts of peak fusion power, attaining 70 percent of breakeven *[25]* and sustaining 10 megawatts for more than half a second *[26]*. For several years JET has been serving as a test-bed for ITER technologies. It now has a magnetic arrangement similar to ITER's and tungsten and beryllium inner-vessel structures that will facilitate learning how to mitigate plasma instabilities.

JT-60SA: Japan is constructing JT-60SA as an upgrade to its flagship fusion research site operating since 1985. The new tokamak – roughly the size of JET – will use superconducting coils and is another device that will enable ITER-relevant research ahead of ITER's first experiments.

EAST: In the past decade China has developed internationally important superconducting fusion devices. China's Experimental Advanced Superconducting Tokamak (EAST) at the Institute of Plasma Physics in Hefei was an early superconducting experimental device *[27];* it achieved pulses lasting up to 1,000 seconds – though not with a D-T plasma *[28]*. Because its magnetic configurations and heating schemes are similar to those at ITER, it is expected to provide another experimental test bench for ITER, especially for studying plasma stability.

Wendelstein 7-X (W7-X): The largest stellarator in the world has just begun to operate in Greifswald, Germany. Known as W7-X, it is tightly optimized. Its superconducting magnets will enable testing of continuous operability for 30 minutes, although not with output power exceeding input power. W7-X was years over schedule and budget due to the daunting technical precision necessary. A non-superconducting stellarator predecessor to W7-X, called the National Compact Stellarator Experiment (NCSX) and located at Princeton University, was cancelled in 2008 – a U.S. budget decision driven by cost overruns and underestimated technical difficulties *[29]*.

Tokamaks and stellarators are being pursued in parallel. Each has its advocates, and W7-X has become the stellarator's strongest entry in the competition. The pivot toward the tokamak as a result of its relative simplicity reveals the path dependency in fusion research because of costs and long lead times in project construction. Tokamaks have a head start toward commercialization and may stay in the lead because of the experience that is likely to be gained from troubleshooting and then running ITER. Conceivably, if ITER struggles and W7-X excels, the post-ITER planning could involve a larger stellarator *[30]*.

Post-ITER demonstration reactors

Although it is possible that ITER's technical goals will not be realized because the burning plasma reveals intrinsic complications, leaders of the fusion research community are planning facilities for the period beyond 2030 that would create a bridge between ITER and an eventual commercial reactor. The bridge, called DEMO, would take the form of a demonstration experiment – or series of experiments. According to these inchoate but ambitious plans for 2030 and beyond, DEMO would feature near-continuous operation, tritium breeding, 30-50 fold return on energy input, and capabilities to convert fusion heat to electric power. There is no consensus on whether DEMO would be an international collaboration like ITER *[31]*.

Simultaneously with the planning in the framework of DEMO, several nations are already making plans for single-nation post-ITER experiments. In part, they are responding to ITER's long lead time and the international contestation over its costs and siting. China is planning the Fusion Engineering Test Reactor (CFETR) as a stepping-stone between ITER and DEMO *[32]*, nearly at ITER's scale *[33]* and intends to integrate capabilities for generating power *[34]*. South Korea is planning to develop the K-DEMO, a post-ITER reactor aspiring to operate at commercial scale *[35]*. The potential redundancy of these large proposed experiments – with each other and with DEMO – could create new political tension and unsustainable budgets. If at some point commercial viability emerges, collaboration among nations may fade in favor of competition for market share, but for now international collaboration is the norm.

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