J-Fusion
Fusion Energy White Paper

June 6, 2025 version

Introduction

The Japan Fusion Energy Industry Council (J-Fusion) was established in March 2024 with the mission to “bring innovation to energy systems in Japan and throughout the world by creating a fusion energy industry, and contribute to humanity's development with stable and clean energy for the future." J-Fusion aims to achieve this through the industrialization and commercialization of fusion energy.

Japan has long been a global leader in fusion energy research and development. The creation of a domestic fusion energy industry, and the strengthening of its foundations, are critical to maintaining and expanding this leadership. Decades of continuous R&D, coupled with growing societal demand for sustainable energy solutions, have generated unprecedented momentum towards the commercialization of fusion energy. Going forward, in-depth dialog between the public and private sectors will be vital so that stakeholders can collaborate in growing the industrial infrastructure and the number of fusion-related businesses.

This white paper was created to promote awareness and understanding of fusion energy. It provides foundational knowledge—the basic principles of fusion energy, an overview of R&D efforts in Japan and measures to ensure these efforts are conducted safely, and referential case studies from the US, UK, and France. Furthermore, it presents perspectives and guidelines to support the private sector as they develop and deploy commercial fusion energy systems.

We hope this white paper will help companies and organizations further their understanding of the fusion energy sector, catalyzing discussion on the development, implementation, and dissemination of fusion energy throughout Japan.

Safety & Standards Working Group
Japan Fusion Energy Council

Contents

1. What is Fusion Energy?

1.1 What is Fusion Energy?

Fusion reaction is the process that powers the sun and other stars, generating energy by fusing (smashing together) light atomic nuclei into heavier ones.[1]

Done properly, a massive amount of energy can be converted from small number of nuclei, as described in Einstein's famous equation, $E = mc^2$.[a]

To understand how powerful fusion energy is, we can compare it to burning coal (carbon): burning one carbon atom from coal produces about 4 electronvolts (eV) of energy. The fusion reaction of a single deuterium and tritium atom produces 17.6 million eV (Figure 1-1), about 4 million times more energy per reaction compared to burning fossil fuel.[2]

Fusion reaction is often generated by fusing deuterium and tritium, isotopes of hydrogen chosen for their light weight. Both isotopes have one proton, with the only difference being the number of neutrons: deuterium has two, and tritium has three. This is the most achievable fusion reaction on Earth using current technology, creating a helium nucleus, a neutron, and 17.6 million eV of energy.

In addition to deuterium-tritium fusion reaction, there is active research in other fusion pairs such as deuterium-deuterium, deuterium-helium-3, and proton (light hydrogen or hydrogen)-boron-11, but these alternatives currently require more demanding conditions to achieve fusion.

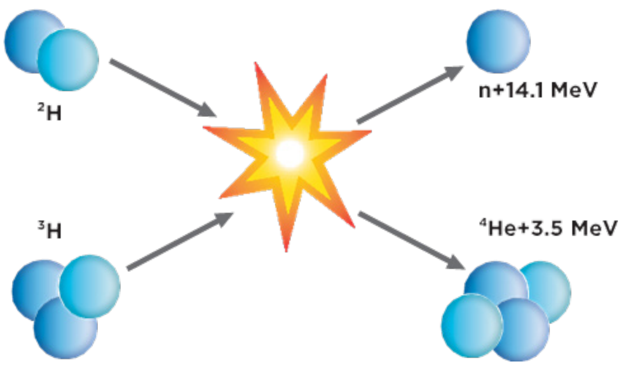

Figure 1-1 Fusion energy generated by fusing deuterium and tritium[3]

[a]The equation expressing the equivalence of mass and energy. E: Energy, m: Mass, c: Speed of light

A fusion reaction can only happen when two positively charged atomic nuclei are brought close enough for the strong force to overcome the electrostatic force pushing the atoms away from each other. This is usually achieved in extremely high-temperature, high-pressure environments.

At high temperatures, the electrons in an atom have enough energy to break free from their nuclei. This creates a hot, charged plasma where the atomic nuclei can potentially fuse with each other.[4]

A high pressure environment helps the nuclei in the plasma fuse by essentially squeezing them together; this happens naturally in the sun as its large size results in a gravitational pressure 260 billion times that of Earth.[5] We cannot replicate the sun's gravity on Earth, so deuterium and tritium were chosen as the fusion materials as they are easier to fuse than the pure hydrogen-hydrogen reactions done by the sun.

Other research into fusion energy has led to techniques like using magnetic confinement to trap the hot plasma, and ways to increase pressure by imploding the fusion fuel. The greatest technical challenge in achieving practical fusion power generation is getting more energy out than the amount put in, but research is progressing at a rapid pace.

1.2 The Potential of Fusion as an Energy Source

Fusion energy is expected to become a foundational power source in the future: it is a clean source of energy that is unaffected by weather and does not emit CO_2. The heat generated from fusion energy can be used in various ways, such as biomass hydrogen production, carbon fixation, synthetic liquid fuel generation, and biomass CCS (Carbon dioxide Capture and Storage). This is why fusion energy is believed to be essential in creating a net-zero emissions, sustainable society.

2. Comparison of Fusion Energy and Nuclear Power

2.1 Fundamental Differences Between Fusion Energy and Nuclear Power

Fusion reactions are often compared to nuclear fission reactions (used in conventional nuclear power generation), so it is key to have a good understanding of the differences between the two. Fusion reactions take light atomic nuclei and fuse them into heavier nuclei, like helium-4. Nuclear fission reactions are the opposite; they involve splitting heavy atomic nuclei (such as uranium or plutonium) into multiple lighter atomic nuclei. Both fusion and fission can generate massive amounts of energy, enough for use on a commercial scale, but there are significant differences in terms of the reaction conditions, reaction products, fuels used, and energy efficiency.

Looking at the reaction conditions, temperatures exceeding 100 million degrees Celsius are needed for fusion reactions, whereas nuclear fission reactions only reach several hundreds of degrees. Fusion reactions are also not self-sustaining, and can be immediately stopped by cutting the fuel supply.

This is the opposite of a nuclear fission reaction, a chain reaction that must be controlled through constant monitoring. This monitoring continues even after the reactor is shut down, requiring multiple safety measures need to be in place.

In terms of reaction products, fusion reactions primarily produce particles such as helium and tritium nuclei, neutrons, and protons. Helium is a harmless element, but tritium is a radioactive isotope that emits weakly-penetrating electrons and must be handled safely. Other radioactive products that require safe handling include the materials used to build the walls of the fusion machine, which are activated by the neutrons generated from the fusion reaction.

Nuclear fission reactions generate highly radioactive fission products, requiring long-term storage and management. Nuclear fissions reactions also activate the surrounding structures, and these radioactive materials also need to be carefully managed.

As to the fuel used in the reaction, fusion reactions use deuterium, which is stable and relatively easy to handle, and tritium, which is radioactive and requires careful handling. Deuterium and lithium (a raw material for tritium) are abundantly found in seawater, providing a potential source for fusion power generation.

Nuclear fission reactions use uranium and plutonium, which are radioactive and require special handling measures. As long as they are handled properly (for example remotely from another room), the radiation risk is extremely low. Both of these elements are currently mined from the earth, but there is research into extracting the elements from more sustainable sources, such as seawater.

Finally, we compare the energy efficiency. Nuclear fission reaction generates energy equivalent to around 1.6 tons of oil from 1 gram of uranium, whereas fusion reaction can extract energy equivalent to about 8 tons of oil from 1 gram of deuterium and tritium.

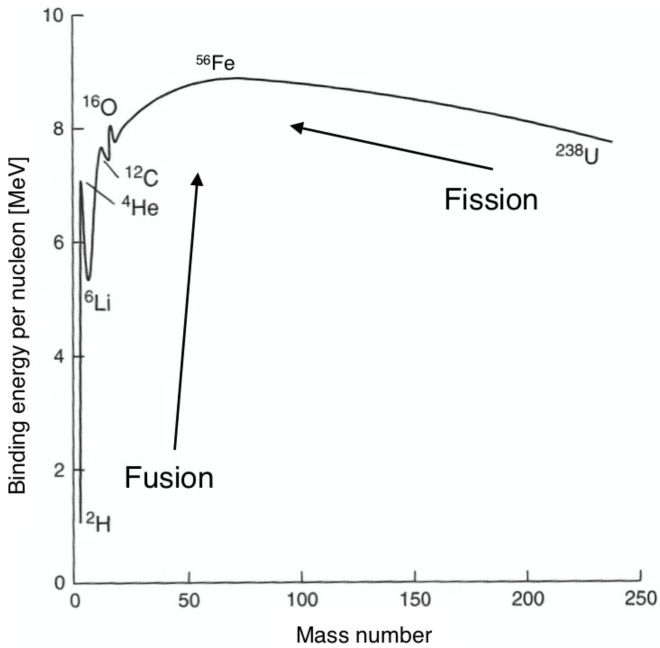

Figure 2-1 Binding energies of elements in fusion and nuclear fission reactions[6]

This is illustrated in Figure 2-1, where the vertical axis represents the binding energy per nucleon for a nucleus, and the horizontal axis represents the atomic number. Binding energy is the energy required to separate one nucleon (a blanket term for protons and neutrons) from the atomic nucleus, meaning the higher the binding energy, the more stable the nucleus. Energy is generated if the reaction products have a higher binding energy than the initial elements. Nuclear fission reaction splits a larger element into several smaller elements to reach stability, whereas fusion reaction does the same by merging several smaller elements into a larger element. Going back to Figure 2-1, we can see that the change in binding energy is much greater for a fusion reaction compared to a nuclear fission reaction.

2.2 Features of Fusion Energy Machines

2.2.1 Typical Types and Characteristics of Fusion Energy Machines

Fusion energy machines can be categorized into two approaches: magnetic confinement and inertial confinement, and various types of machines have been developed using these approaches (Figure 2-2).

(1) Magnetic Confinement Approach

Uses a magnetic field to confine the plasma, with the following being the main types.

1) Tokamak

- **Plasma Confinement:**

  By combining the poloidal magnetic field created by passing plasma current through the plasma and the toroidal magnetic field produced by toroidal field coils, a helical-shaped magnetic field (twisting of magnetic field lines) is formed to confine the donut-shaped plasma.[7]

- **Operating Characteristics:**

  To maintain a steady current in the plasma, advanced plasma control techniques such as pressure distribution control and current drive through external heating are required.

- **Extracting Energy:**

  The energy released by fusion reactions is primarily captured by blankets placed around the plasma (see Section 2.2.2). The blanket absorbs high-energy neutrons generated by the reaction and recovers their kinetic energy as heat. As neutrons collide with blanket materials, they thermalize and transfer their energy to the blanket structure. The recovered thermal energy is carried away from the blanket to a turbine via two-staged coolant loops to produce electricity. Additionally, the blanket uses materials containing lithium, which reacts with neutrons to produce tritium.

- **Technological Progress:**

  The ITER project (see section 3.2.3) is an international project that is currently underway. In Japan, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) identified the Tokamak as the most developed fusion type and the leading candidate for the nation's first demo plant in its 2017 report on "Promotion of Research and Development of Prototype Fusion Reactors." A major challenge for tokamaks is the phenomenon of disruption[b], where plasma confinement suddenly collapses, potentially damaging machine components. While disruptions are particularly critical in tokamaks, plasma instabilities are an inherent issue across all fusion designs, making stability control a universal challenge in fusion development.

2) Stellarator (Helical)

- **Plasma Confinement:**

[b] Disruption is when the magnetic surface confining the plasma breaks down, causing the plasma current to rapidly decay and disappear. Causes include excessive plasma density and excessive pressure.

Like tokamaks, stellarators confine plasma in a donut-shaped configuration. However, unlike tokamaks, the twist in the magnetic field lines is generated by the shape of the external coils themselves, rather than by driving a current through the plasma.

- **Operating Characteristics:**

  Because stellarators do not rely on plasma current for confinement, they avoid current-driven instabilities and offer inherently steadier plasma conditions. This makes it easier to sustain plasma for long periods, giving stellarators a potential advantage for continuous (steady-state) operation compared to tokamaks.

- **Extracting Energy:**

  As with tokamaks, the energy released by fusion reactions is captured by a surrounding blanket system. This energy is converted into electricity using a secondary coolant, such as steam, to rotate turbines that drive generators.

- **Technological Progress:**

  Major experimental stellarator machines include Japan's Large Helical Device (LHD) (see section 7.1.2.) and Germany's Wendelstein 7-X (W7-X). While stellarators have more complex coil structures than tokamaks—making design, fabrication, and assembly more challenging—recent progress in precision machining, superconducting magnet technology, and computational simulations has significantly accelerated their development, particularly in Japan, Germany, and the United States.

3) Mirror

- **Plasma Confinement:**

  Unlike the donut-shaped tokamaks or stellarators, a mirror-type fusion machine has a linear magnetic field structure that confines the plasma by reflecting it back and forth at both ends of the machine, like a mirror.

- **Operating Characteristics:**

  The relatively simple design of a mirror machine gives it an advantage over tokamaks and stellarators. Despite this, the ends of the magnetic field introduce significant energy and particle losses, requiring a higher density and better confined plasma before fusion reactions can occur.

- **Extracting Energy:**

  The shape of the machine allows high-energy fusion products to escape its ends, allowing electricity to be potentially generated through electromagnetic induction (direct power generation).

- **Technological Progress:**

  R&D into mirror machines are being led by Tsukuba University, the University of Wisconsin in the US, and private startup companies.

4) Field-Reversed Configuration (FRC)

- **Plasma Confinement:**

  In a FRC machine, plasmoids (plasma masses) start at the ends of the machine and launched towards each other. The plasmoids collide in the center chamber of the machine to form a plasma, and the poloidal magnetic field generated by the plasma confines it to this chamber, raising the temperature and pressure to the levels required for fusion. Research is being conducted on methods to maintain the plasma by either streaming in ions or through rapid pulsed injection.

- **Operating Characteristics:**

  The main advantages of a FRC machine are its ability to confine high-temperature, high-density plasma with a small external magnetic field. The machine itself is also relatively simple compared to tokamak and stellarator designs. However, the technology is still in its infancy, so further improvements in plasma performance and advancements in plasma maintenance and continuous irradiation technology are necessary before it can be capable of creating sustained fusion reactions.

- **Extracting Energy:**

  Various methods to extract energy from FRC machines are being explored, such as directly converting the kinetic energy from the fusion reaction into electricity, eliminating the need for a turbine. In addition to the D-T fusion reaction, safer alternative fuels such as boron-11 and a proton (which does not produce a neutron) are being considered.

- **Technological Progress:**

  Start-up companies in the US and Nihon University in Japan possess FRC equipment and are making advances in R&D.

(2) Inertial Confinement Method

This method uses lasers or similar means to irradiate fuel pellets, compressing the fuel through the reaction force from blowing off the outer shell, and inducing a fusion reaction in a short period of time. The main types include the following.

1) Laser Fusion

- **Reaction:**

  In laser fusion, a small spherical fuel pellet is irradiated simultaneously from multiple directions with high-power laser beams. The intense laser energy compresses the pellet uniformly, causing it to implode and reach the conditions necessary for a fusion reaction.

- **Operating Characteristics:**

  For laser fusion to become a practical power generation system, it must achieve repeated implosions at a high frequency—on the order of ten or more times per second. While short-duration, high-density reactions have been demonstrated, achieving stable and continuous operation remains a major challenge. In particular, perfectly uniform implosion of fuel pellets is required, demanding significant advances in laser control, targeting precision, and fuel pellet technology.

- **Extracting Energy:**

  The thermal energy generated by the fusion reaction is absorbed by a blanket placed around the implosion chamber. This heat is used to generate steam, which drives a turbine, thereby powering a generator to convert it into electricity.

- **Technological Progress:**

  Research in laser fusion is being carried out at major facilities such as the National Ignition Facility (NIF) in the United States and Gekko XII at Osaka University in Japan.

2) **Quantum Beam Fusion**

- **Reaction:**

  Fusion reactions are induced using high-energy beams, such as heavy ion beams, to heat and compress the target.

- **Operating Characteristics:**

  Continuous and efficient energy input is made possible through quantum beams.

- **Extracting Energy:**

  As with other methods, the goal is to collect the thermal energy generated by fusion reactions using a blanket, produce steam, and then drive turbines and generators to convert it into electricity. However, specific technical details have not yet been established.

- **Technological Progress:**

  The project is in its initial research phase, with the outlook of establishing basic technologies.

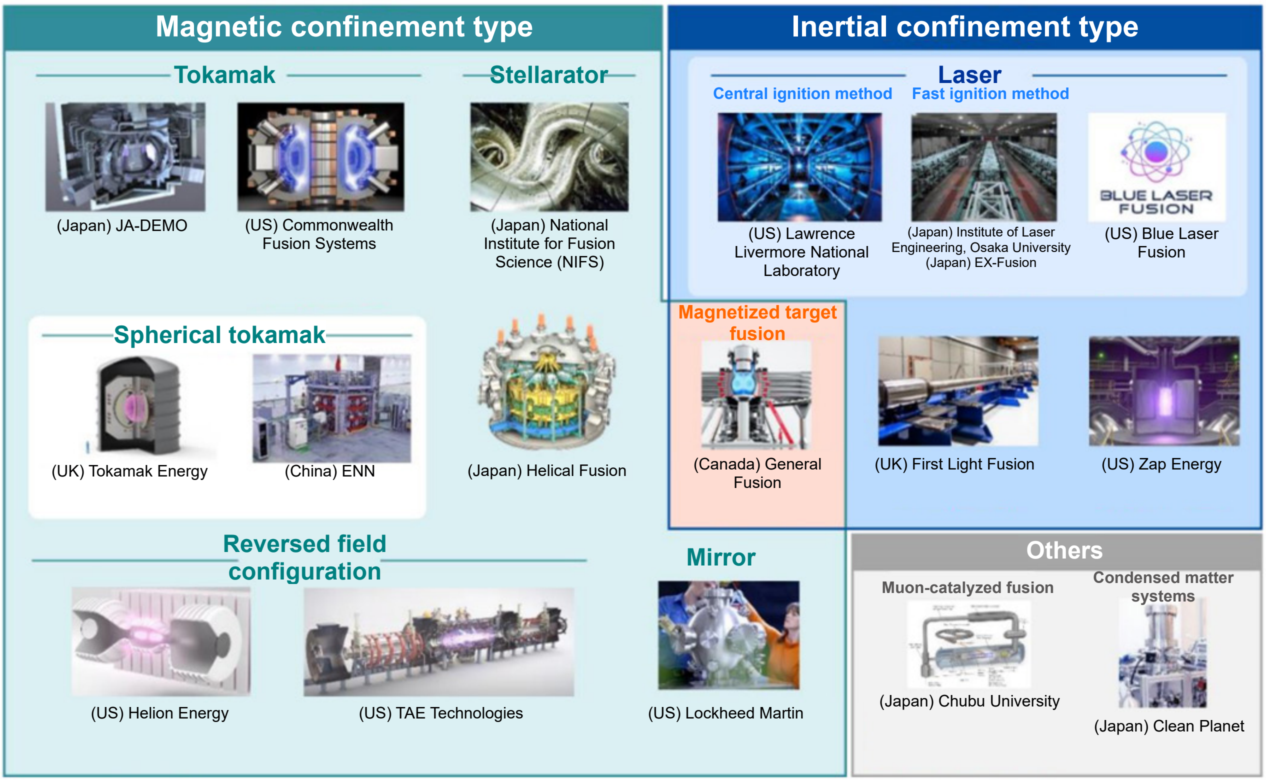

Figure 2-2 Main types and configurations of fusion machines[8]

2.2.2 How Fusion Energy Plants Generate Power (Tokamak and Stellarator Fusion Machines)

Generating power from fusion reactions involves the conversion of the energy from the superheated plasma into electricity. This plasma reaches temperatures above 100 million degrees Celsius, and contains deuterium, tritium, and their reaction products helium and neutrons.

The neutrons carry 80% of the energy generated by the fusion reaction. The neutrons exit the plasma containment as they are uncharged and therefore not affected by the magnetic field of the fusion machine. These high-energy neutrons are then absorbed by blankets installed on the inner walls of the fusion machine's vacuum vessel. The neutrons transfer their kinetic energy to the blanket material and heating it up. This heat is used to drive a turbine, which in turn powers a generator to produce electricity. This is similar to the energy conversion processes employed in conventional nuclear or thermal power plants (Figure 2-3).

The remaining 20% of the energy generated by the fusion reaction is carried by the helium-4 nuclei (alpha particles), which carry a positive charge and remain confined in the plasma. These alpha particles collide with other particles in the plasma to generate heat, helping maintain the high temperatures needed to sustain the fusion reaction. However, alpha particle heating alone is not enough to sustain the fusion reaction, resulting in the need for additional external heating systems such as radio-frequency (RF) and neutral beam injection (NBI) systems. The alpha particles exit the system through a divertor, which controls the purity of the plasma by separating them from the fuel.

On the topic of sourcing fuel for deuterium-tritium reactions, deuterium can be extracted in large quantities from seawater. However, tritium must be bred inside the fusion machine. This is achieved by having neutrons generated from the fusion reaction react with lithium. Similar to deuterium, lithium can be extracted from seawater as well as mined from salt lakes and mineral ores. Theoretically, the neutrons generated from the fusion reaction can generate tritium atoms in a one-to-one ratio. Practically, this does not occur as neutrons are lost when they collide with the reactor structures or leak through heating ports. This means that the number of tritium atoms that can be generated from one fusion reaction (the breeding ratio) is less than one. To compensate, neutron multiplier materials like beryllium and lead are incorporated into the blanket to increase the number of neutrons available for tritium breeding.

There is active research in increasing the breeding efficiency, with a particular focus on the use of lithium-6 isotopes in blanket coolant. As only 7.5% of naturally occurring lithium is lithium-6, developing technologies for the large-scale separation and enrichment of lithium-6 is key to ensuring a sustainable tritium fuel cycle (Figure 2-4).

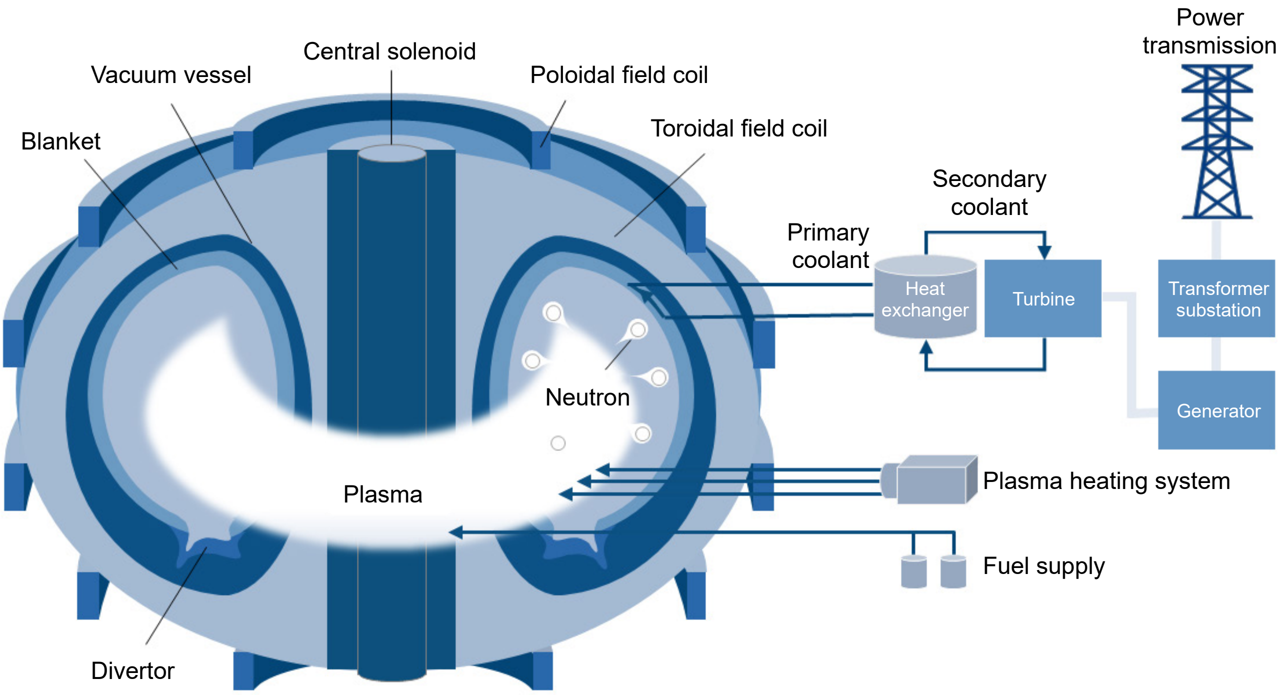

Figure 2-3 Mechanism of tokamak-type fusion power generation

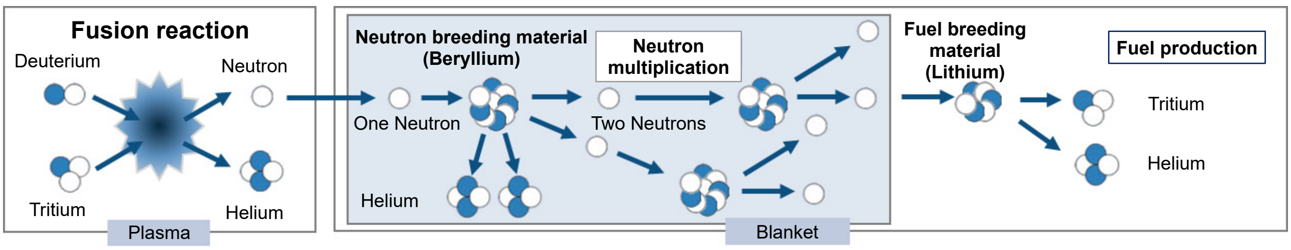

Figure 2-4 Fusion reactions and tritium breeding

2.2.3 Safety Features Related to Fusion Facilities

Fusion energy facilities are clean in that do not produce greenhouse gases, but they do produce relatively short-lived radioactive materials in structural metals such as stainless steel, which are activated by the neutrons from reactions like deuterium-tritium (D-T) fusion. It is critical that measures be taken to manage this waste safely. The main types of waste that need to be managed include structural materials activated by neutrons, and equipment contaminated by these activated materials and tritium from the fuel.

Unlike the waste from nuclear fission plants, fusion energy does not produce spent fuel requiring decay heat removal systems. While the neuron-activated components do retain residual heat, the heat density is much lower than when the facility is running. Current design studies are working to engineer blankets and other components in ways where even if external cooling stops working after a fusion machine is shut down, the components will not be hot enough to exceed the melting point of the structural metals.

Another safety feature of fusion energy facilities is their resilience to disasters and accidents. Fusion reactions are not chain reactions, and only occur when the necessary fuel is supplied and conditions (such as temperature and pressure) are maintained. So even if a disaster disrupts the power grid, interrupts the fuel supply, or damages the main vacuum vessel, the fusion reaction would automatically and rapidly shut down.[9]

2.2.4 Handling of Radioactive Waste Generated from Fusion Plants

Nuclear fission facilities (nuclear power plants) generate highly radioactive waste[c] as a result of processing spent nuclear fuel,[10] which requires long-term isolation and storage. Nuclear waste contains fission products such as iodine-131, cesium-137, and strontium-90, radioactive isotopes noted for their impact on the human body and ease of contaminating the environment.[11] Fusion plants, however, produce helium-4 and neutrons as products of the deuterium-tritium reaction, which shows the most promise of the fusion reactions. This also applies to other fusion pairs such as deuterium-deuterium, deuterium-helium-3 reactions, and proton-boron-11 reactions. In addition to helium-4 and neutrons, fusion reactions may also produce helium-3,[d] tritium, and protons, (Table 2-1), but the main product is non-radioactive helium.

[c] Highly radioactive waste generated when reprocessing spent fuel
[d] Helium-3 is an extremely rare helium isotope with a relative abundance of 0.0001%.

Table 2-1 Typical reactions used in fusion energy[e]

$D + T \rightarrow {}^{4}He(3.52MeV) + n(14.06MeV)$
$D + D \rightarrow {}^{3}He(0.82MeV) + n(2.45MeV)$
$D + D \rightarrow T(1.01MeV) + p(3.03MeV)$
$D + {}^{3}He \rightarrow {}^{4}He(3.67MeV) + p(14.67MeV)$
$p + {}^{11}B \rightarrow 3\ {}^{4}He(Total\ 8.7MeV)$

The deuterium-deuterium reaction produces tritium, a radioactive isotope that emits relatively low-energy beta particles and has a half-life of 12.3 years. This isotope is immediately used to sustain the fusion reaction, and most private and public institutions designing fusion energy plants actually include an outer blanket that can produce tritium through lithium-6. The lithium-6-containing blankets absorb neutrons to produce helium-4 and tritium. These neutrons come from the fusion reaction and multiplied by interacting with beryllium. This means that the primary radioactive isotope in a fusion reaction, tritium, can be fed back into system if handled safely, and steady progress has been made over the last half century in developing system designs and procedures for safe handling.

The neutrons generated by fusion reactions can activate the inner wall of the vacuum vessel[12]; this can create radioactive waste when replacing blankets, divertors, and other equipment during regular maintenance. Due to this, materials currently in use or under consideration for constructing the vicinity of fusion machine cores are either resistant to activation, or can lose their radioactivity in a relatively short period of time (less than 100 years). Examples of these materials include silicon carbide, boron carbide, graphite, carbon fiber composites, beryllium, tungsten, lithium, low-activation ferritic steel, titanium alloys, vanadium alloys, and high manganese steel. The R&D going into these materials will allow them to be recycled 100 years after the blanket has been replaced (dependent on storage and handling policies), and reach a radioactivity low enough (a surface dose rate of 25 μSv/h) to allow touch by hand 100 years after it has been last irradiated[13].

[e] D: deuterium, T: tritium, p: proton, n: neutron

3. The History of Fusion Energy Development in Japan

3.1 The Position of Fusion Energy Research in Japan

Fusion energy holds an important position in Japan's national strategy as a future clean and sustainable energy source. It is expected to enhance energy security, promote the development of advanced technology, and create related industries. A number of developed countries around the world, including Japan, began research and development into fusion energy in the 1950s, and such efforts had grown into national projects by the 1970s, catalyzed by the oil crisis happening at the time. The 1985 Geneva Summit lead to the creation of an international cooperation framework between Japan, the US, Europe, and Russia, resulting in the launch of the ITER project in 1988. ITER has since become a symbol of international cooperation.

The private sector for fusion energy development has also seen rapid growth in recent years. There is growing competition over leadership in fusion energy technology between US, the UK, China, and other countries around the world. These trends demonstrate that the field of fusion energy is undergoing a transition from international collaboration to competition.

3.2 History of Fusion Energy Development in Japan[14,15]

In Japan, the development of fusion energy began with basic research, with current R&D efforts aimed at practical application. The timeline of Japan's research and development efforts toward realizing fusion energy can be divided into four phases based on the strategies formulated by the Cabinet Office: The First to Third Phase Basic Plans (1969-1974, 1975-1991, and 1992-present), and the Fusion Energy Innovation Strategy (from April 2023 onward).

3.2.1 First Phase Basic Plan (1958–1974)[14,15]

Japan began its theoretical and experimental research into fusion energy in the 1950s under the auspices of various institutions and universities affiliated with the then Science and Technology Agency and the Ministry of Education. A fusion subcommittee was established in the Japan Atomic Energy Commission, and the Science Council of Japan established a Nuclear Issues Committee and a Special Committee on Fusion. Additionally, fusion energy researchers established the Fusion Symposium in 1958 with Hideki Yukawa, who won the Nobel Prize in Physics in 1949, as the chairperson. At the second Geneva Conference in 1958, fusion energy research, which had been conducted secretly around the world, was made publicly known. This would accelerate international research.

In 1959, a report was submitted to the chairman of the Japan Atomic Energy Commission on how to proceed with research and development. There, two plans were proposed: Plan A involved “the cultivation of new ideas and prototype development," and Plan B involved “the construction of medium-sized equipment." Plan A was chosen after much discussion was had over the research policies for the two plans. Consequently, Nagoya University established the Institute of Plasma Research under the former Ministry of Education, and the Japan Atomic Energy Research Institute established a fusion research group under the former Science and Technology Agency as the implementing bodies for both plans.

In 1968, the designation of fusion as part of the Comprehensive Nuclear Energy Plan by the Japan Atomic Energy Commission[16] was an extremely significant event for fusion research in Japan. In 1968–1969, the improved Russian T-3 tokamak had achieved a temperature of 10 million degrees Celsius and a plasma confinement time that was several dozen times what was considered possible at that time. The high temperatures reached by the Soviet tokamak device was confirmed using instruments brought to Moscow by British researchers during the Cold War, making tokamak-type fusion devices mainstream globally. This would surprise researchers around the world and subsequently led to a surge in tokamak research.

At the Japan Atomic Energy Research Institute (JAERI), the JFT-1 (hexapole) torus-type fusion experimental device achieved an energy confinement time approximately 50 times that of the then-expected performance of the Soviet T-3, and the design was further refined when building the JFT-2 and JFT-2a tokamaks. The Plasma Research Institute in Nagoya would also construct the JIPP-1 stellarator, which featured a different design compared to tokamaks.

In 1971, the generation of neutrons through laser fusion was successfully achieved. In 1974, the 5th IAEA (International Atomic Energy Agency) Conference was held in Tokyo, where Japan’s research level was recognized as having reached international standards.

3.2.2 Second Phase Basic Plan (1975–1991)[14,15]

In 1975, the Japan Atomic Energy Commission formulated the Basic Plan for the Second Phase of Fusion Research and Development, and the JAERI began the construction of JT-60. In 1978, under the initiative of the IAEA, a joint project involving Japan, the US, Europe, and the Soviet Union for a collaborative fusion experimental machine (INTOR) was launched. The project continued until 1987.

As a symbolic event marking the end of the Cold War, the Reagan-Gorbachev joint statement in Geneva in 1985 agreed to reduce strategic nuclear weapon arsenals and cooperate in fusion energy development. This would ignite the conceptualization for the International Thermonuclear Experimental Reactor (ITER), conducted from 1988 to 1990 under a four-party system between Japan, the US, Europe, and the Soviet Union.

3.2.3 Third Phase Basic Plan (1992–present)[14,15]

With the collapse of the Soviet Union and the formation of Russia, Engineering Design Activities (EDA) were carried out over a period of nine years starting from 1992. Through the EDA, Japan developed full-scale or partial models of critical ITER components, such as superconducting coils, vacuum vessels, blankets, and divertors.[17,18]

In the late 1990s, critical plasma equivalent condition (using DD fuel, successfully recreating a state equivalent to critical plasma when using actual deuterium-tritium (DT) fuel), and break-even equivalent conversion DT fusion critical plasma equivalent conditions (a state where the energy generated by DT fusion reactions equals the energy inputted to maintain the plasma) were achieved using DD fuel with the JT-60U.[f] These achievements and other advancements led to improved tokamak plasma performance.

In 1992, the Japan Atomic Energy Commission formulated the Third Phase Basic Plan for Fusion Research and Development, defining an experimental fusion machine as the plan's core device.

In 1996, the International Thermonuclear Experimental Reactor (ITER) was making steady progress with its engineering design activities. The Japan Atomic Energy Commission expressed the view that it would be appropriate to position and develop ITER as the experimental fusion machine defined within the Third Phase Basic Plan. The National Institute for Fusion Science (NIFS) completed the Large Helical Device (LHD) as these developments were taking place, successfully incorporating superconducting helical coils and a negative ion neutral beam injector (negative ion NBI or negative NBI), marking continued technological advancements in fusion energy research.

In 2001, a reorganization of central government ministries and agencies led to the formation of the Ministry of Education, Culture, Sports, Science and Technology. In January 2003, the Science and Technology Council of the Ministry of Education, Culture, Sports, Science and Technology formulated a policy on “The Future Direction of Japan's Fusion Research," which emphasized Japan's fusion energy research with four main pillars: tokamak (JT-60U), stellarator (LHD), laser (GEKKO-XII, etc.), and fusion machine engineering (material irradiation).

In the field of tokamak research, the global focus has shifted to the ITER project. In 2005, Cadarache, France was chosen as the construction site for the ITER project. In 2007, as the ITER Agreement and the Broader Approach (BA) Agreement entered into force, full-scale international cooperation commenced.

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[f] Deuterium-tritium are not conducted with the JT-60, and estimates are based on data obtained from experiments using deuterium-deuterium reactions.

In the study of stellarator systems, the LHD has led global research on stellarator systems, achieving experimental results such as high beta values and long-duration discharges throughout the 2000s. In 2017, it made significant contributions to our understanding of plasma and the improvements to control technology, reaching an ion temperature of 120 million degrees in deuterium plasma experiments.

There have been advancements in fusion machine engineering research under international cooperation efforts such as IFMIF/EVEDA (International Fusion Materials Irradiation Facility Engineering Validation and Engineering Design Activities) and JUPITER (Japan-US Program of Irradiation/Integration Test for Fusion Research), with the Council for Science, Technology and Innovation and other bodies promoting the development of technologies that can be used to realize fusion machines.

In 2008, JT-60U was decommissioned to allow it to be modified into the superconducting JT-60SA. In the same year, the Prototype Reactor Design and R&D Coordination Center, the ITER Remote Experimentation Center, and the Computational Simulation Center were established at the International Fusion Energy Research Center (IFERC) located in Rokkasho, Aomori Prefecture. These facilities would conduct the design and R&D of the prototype fusion machine, remote experimentation for ITER, and the development of simulation technologies.[19]

In the 2010s, although the construction of ITER was behind schedule, steady progress was made in creating the facility towards achieving first plasma. In the BA activities, which include ITER and JT-60SA, not only fundamental research, such as core plasma physics and materials science, but also research and development in engineering necessary for completing fabrication projects have been carried out under international cooperation.

JT-60SA achieved first plasma and began experimental operation in October 2023. Additionally, ITER has proceeded with the fabrication and delivery of technically demanding components to the fusion plant site, and all toroidal field coils have been delivered. Meanwhile, manufacturing challenges have emerged with some components, and reviews of the processes are underway.

3.2.4 Fusion Energy Innovation Strategy (April 2023–Present)[20]

Fusion energy is anticipated to be a clean energy source that will contribute to future energy security. This has increased its priority in government policy, prompting leading countries around the world to accelerate their efforts in fusion energy development. Accordingly, the Cabinet Office formulated and published the Fusion Energy Innovation Strategy in April 2023.

The strategy contains the following guidelines: “Position fusion energy as the core in creating new industries and ensure Japan does not miss opportunities to enter the emerging global supply chain competition," “Accelerate the practical application of fusion energy through a multifaceted approach, including industrialization, in addition to the current progress from the ITER Project and BA activities toward prototype fusion machine development," and “Establish an industrial council, promote research and development by startups and related entities, discuss safety regulations, strengthen support for emerging technologies, and implement educational programs."

Simultaneously, there is greater investment in fusion energy ventures, marking the transition from an era of “international cooperation" to "international competition" in the ITER program.[21]

All of this is underlined by a paradigm shift in energy dominance from "resource ownership" to "technology ownership" (Fusion Energy Innovation Strategy). Nations are encouraging investment and providing policy support in order to claim supremacy over next-generation energy generation by becoming the leader in developing the technologies required.[20]

(1) ITER Project[22]

The ITER Project is an international collaborative effort to realize fusion energy and is currently under construction in Cadarache, France. It is the world's largest experimental fusion device and is a joint effort between seven parties—Japan, the European Union (EU), the US, Russia, China, the Republic of Korea, and India—representing a total of 33 countries.

The objective of ITER is to fundamentally resolve energy and environmental issues by establishing the scientific and technological know-how needed to achieve practical fusion energy. This is an international commitment that will be realized through the construction and operation of the ITER experimental fusion device.

The primary goal set for this endeavor is to achieve a plasma that burns with an energy amplification factor (Q value) of 10 or more. For example, if the input energy was 50 MW, the fusion machine should output 500 MW, ten times the input (Table 3-1). There are also technical goals to demonstrate Japan's fusion engineering technologies, such as superconducting coils (magnetic field generation devices) and heating devices.

Demonstrating that fusion energy is feasible through scientific theory and practical technology is regarded as being of utmost importance, and the ITER experimental fusion machine will unlock progress in both fields.

The ITER project officially commenced construction in 2007 following the creation of the ITER Organization and signing of the ITER Agreement. Initially, the plan was to commence operations in 2018, though the unclear integration conditions stemming from the complex allocation and delivery of procured components, the emergence of additional components, technical challenges, design revisions, the impact of the COVID-19 pandemic, and other factors, the schedule for first plasma has been delayed to 2034 (as of 2025). Consequently, the commencement of fusion burning operations using deuterium-deuterium (D-D) fuel has been rescheduled to 2035, and operations with deuterium-tritium (D-T) fuel are now planned to begin in 2039.

ITER employs a tokamak-based magnetic confinement approach and possesses the following technical characteristics.

Table 3-1 Technical characteristics of the ITER fusion experimental facility[23]

Fusion thermal output	500 MW (700 MW)
Q value (Fusion thermal output/external heating input)	≥ 10
Average 14 MeV neutron wall loading	0.57 MW/m^2 (0.8 MW/m^2)
Combustion time driven by induced current	≥ 400 seconds
Major radius (R)	6.2 m
Minor radius (a)	2.0 m
Plasma current (Ip)	15 MA (17 MA[1])
Elongation ratio (κ_{95}) at the 95% magnetic flux surface/separatrix	1.70/1.85
Angle (δ_{95}) at the 95% magnetic flux surface/separatrix	0.33/0.49
Safety factor (q_{95}) at the 95% magnetic flux surface	3.0
Toroidal magnetic field (BT) at radius 6.2 m	5.3 T
Plasma volume	837 m^3
Plasma surface area	678 m^2
Input power via external heating and electrical current drive device	73 MW[2]

Participant countries in the ITER project are responsible for the manufacturing and procurement of equipment, while the ITER organization is tasked with the overall assembly of the device. As a quasi-host nation, Japan is responsible for the procurement of advanced core equipment for ITER and is jointly advancing the Broader Approach (BA) Program with the EU.

This program, utilizing JT-60SA (a tokamak-type superconducting plasma experimental device) installed in Naka City, Ibaraki Prefecture, Japan, is primarily aimed at supporting research for the ITER project, conducting advanced complementary research for prototype fusion machines and training the talent for them. It is being carried out in parallel with the ITER project.

Japan is procuring the following core equipment as part of the ITER project.[24]

- Superconducting conductor for the central solenoid
- Superconducting toroidal magnetic field coils
- Tritium plant facilities
- Blanket remote maintenance equipment
- Divertor
- High-frequency induction heating equipment

- Neutral beam injection heating device
- Measuring instruments

The ITER project is extremely important to Japan's development strategy, as it is the final stage before realizing the first prototype fusion machine capable of power generation. In line with the progress of the ITER project, it is necessary for domestic fusion energy research institutions, industry, and universities in Japan to promote extensive research and technological development, including innovations required for the prototype fusion machine, in response to the policy and institutional support from the Japanese government.

(2) Major Projects within Japan[25]

Japan is conducting several fusion energy-related projects with a push towards international collaboration and private sector participation (Table 3-2).

The following list of domestic projects is based on the results of a survey conducted primarily on projects disseminated by the Cabinet Office and member companies of J-Fusion, so it is not a comprehensive look at all fusion energy projects in Japan.

Table 3-2 List of major domestic projects (1/2)

Furnace Type		Project and Device /Corporation	Overview
Magnetic confinement method	**Tokamak**	JT-60SA (QST: National Institutes for Quantum Science and Technology)	The superconducting tokamak fusion experimental device operated by QST. Complements the ITER project and advances plasma research.
		FAST Project (Planned for construction)	The fusion power test plant construction project led by Starlight Engine. It aims to demonstrate power generation technology by adopting a low aspect ratio tokamak device utilizing high-temperature superconducting coils.
		QUEST (ST format, Kyushu University)	The spherical tokamak (ST) fusion device being developed by Kyushu University aiming for sustained plasma confinement over extended periods of time.
	Stellarator	LHD (NIFS)	One of the world's largest stellarator devices operated by the National Institute for Fusion Science (NIFS), where advancements in research on magnetic confinement methods are being made (scheduled for decommissioning in fiscal year 2025).
		Helical Fusion’s Helix program (Planned for construction)	A startup that has inherited the research achievements of the NIFS. It aims to develop steady-state fusion by leveraging proprietary high-temperature superconducting technology and blanket-divertor technology.
	Mirror	GAMMA10 (University of Tsukuba)	A mirror-type magnetic confinement device operated by Tsukuba University. This is a linear device used for studying plasma heating and confinement characteristics.
	FRC	FAT-CM (Nihon University)	A field-reversed configuration (FRC) type magnetic confinement device operated by Nihon University. It is capable of achieving supersonic merging of plasmoids.
	FRC-Mirror	LINEA Innovation (Planned for construction)	This startup aims to realize a method that combines FRC with a mirror-type magnetic field, targeting the development of an advanced fusion machine that does not generate neutrons.

Table 3-2 List of major domestic projects (2/2)

Furnace Type	Project/Company	Overview
Inertial confinement method (Laser)	Gekko XII (Osaka University)	A laser fusion device operated by Osaka University. Utilizing the inertial confinement method, the fuel is compressed and heated with high-power lasers.
	EX-Fusion (Planned for construction)	A startup aiming to commercialize laser fusion for civilian use. It has conducted research on high-speed ignition systems.
	Blue Laser Fusion (Planned for construction)	While developing a pioneering high average power laser, it aims to realize laser fusion energy.

(3) Trends in the Industrial Sector

Domestically, both large corporations and startups are showing a greater interest in fusion energy development. Major corporations such as Mitsubishi Heavy Industries, Hitachi, and Toshiba Energy Systems & Solutions are focusing on the manufacturing of fusion machine components and the development of superconducting or other related technologies. These companies pay a particularly important role within the ITER program and domestic fusion energy-related projects in Japan, as they provide the advanced technologies required for these projects.

Domestic startups such as Kyoto Fusioneering, EX-Fusion, and Helical Fusion are powering research and development towards quickly achieving practical fusion energy, leveraging their proprietary technologies to make advances in fusion machine system design, laser fusion technology, and core material development. Both domestic and international venture capital firms and business enterprises are investing more into these startups, providing the funding to foster new technological innovations.

We can see how major corporations and startup companies are leveraging their respective strengths to further fusion energy technologies. Coupled with governmental support, the domestic fusion energy industry is achieving accelerated growth.

A fusion machine is comprised of components made using a wide range of advanced technologies (Figure 3-1). The complexity involved means that within Japan, many companies are involved in the development and manufacturing of critical components such as superconducting coils, blankets, divertors, vacuum vessels, and plasma heating devices.

The list of fusion components manufacturing companies below only covers J-Fusion member companies, and is not a comprehensive list of all domestic manufacturers in the fusion industry.

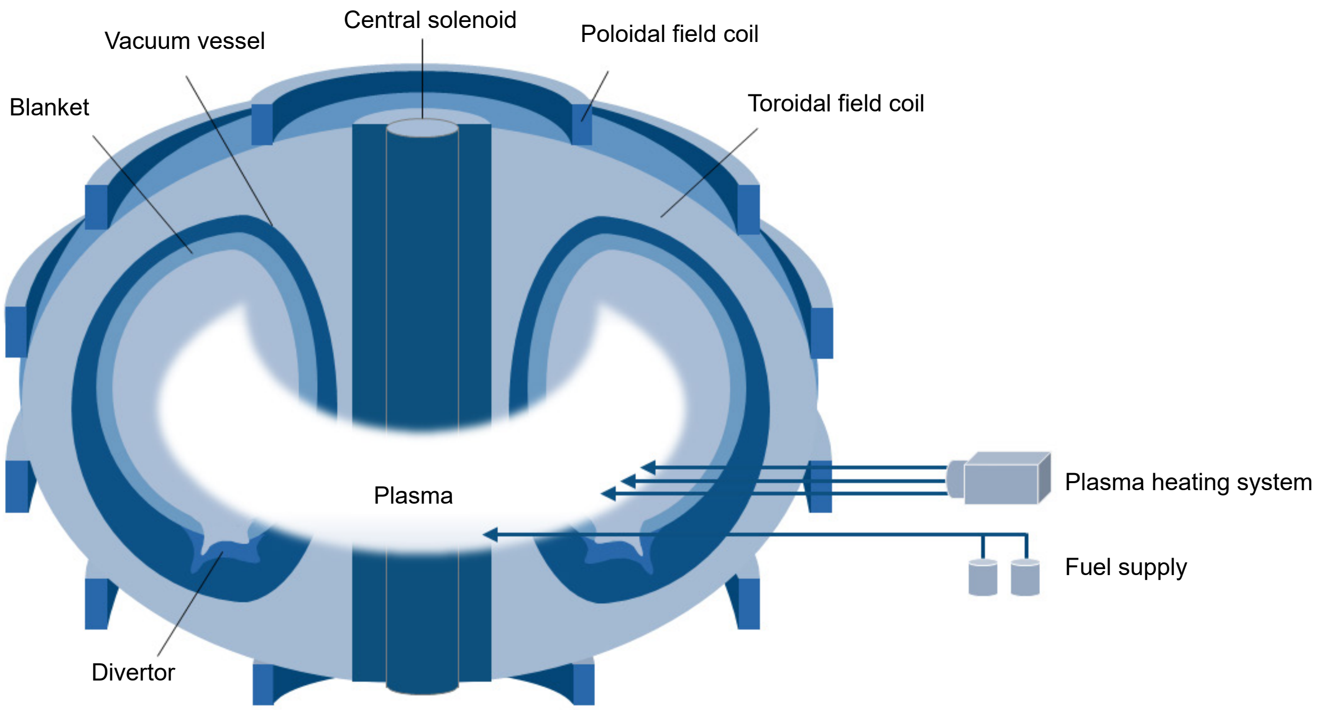

Figure 3-1 Major components of a fusion machine (tokamak type)

1) Manufacturing of Coils and Superconducting Technology

In the magnetic-confinement fusion approach, superconducting coils form the core technology that enables plasma confinement within strong magnetic fields. The Japanese industry has long played a leading role in this field: companies such as Mitsubishi Heavy Industries, Hitachi, Mitsubishi Electric, Toshiba Energy Systems & Solutions, and Nippon Steel Engineering have been responsible for manufacturing critical components—including the central solenoid (CS) and toroidal field (TF) coils—as part of Japan's procurement contributions to ITER.

More recently, attention has turned to the development of coils using high-temperature superconductors (HTS), regarded as the next generation of superconducting materials. Japan also has strong capabilities in this area: Fujikura and Furukawa Electric (together with its US subsidiary SuperPower) have established proven track records in HTS tape development, while Faraday Factory Japan is also supplying HTS tapes to the market. Building on this supply chain, Helical Fusion is advancing proprietary coil technologies that apply HTS tapes to the design of innovative fusion magnets.

2) Blanket and Fuel Circulation Technology

The blanket is a critical component that absorbs high-energy neutrons generated by fusion reactions, converting them into heat through neutron breeding. The neutrons then produce the tritium needed to fuel the fusion process by reacting with the lithium loaded into the blanket.

In Japan, Helical Fusion, Kyoto Fusioneering, and other startups have outlined their approaches to liquid metal blankets. Kyoto Fusioneering's UNITY-1 project, which includes conducting liquid metal loop tests at a mock plant, aims to establish power generation technology.[26] Helical Fusion, in collaboration with Sukegawa Electric Industry, has developed the liquid metal blanket device GALOP[27] and has commenced testing for blanket and divertor applications. Additionally, QST is leading the development of the ITER Test Blanket Module (TBM), with Toshiba Energy Systems & Solutions and Mitsubishi Heavy Industries involved in its manufacturing and testing.

Regarding fuel cycle technology, Kyoto Fusioneering is developing a fusion fuel cycle system that involves the recovery, separation, and reuse of tritium and hydrogen isotope gases used in fusion machines. Furthermore, fusion energy startups originating from QST, such as LiSTie and MiRESSO, are developing technologies related to lithium recovery for fuel purposes and beryllium production for neutron breeding materials. These efforts are expected to enhance the sustainable supply and economic efficiency of fusion fuel.

3) Divertor and Plasma-Facing Components

The equipment installed inside the fusion machine (within the vacuum vessel) and facing the plasma directly are referred to as the plasma-facing components. They include devices such as the divertor, first wall, and limiter, with the divertor subject to the most extreme conditions within the vacuum vessel of a fusion machine.[28] The divertor is the component within the fusion machine that comes into contact with plasma and must maintain durability under extremely high-temperature conditions.

In ITER, the plasma-facing divertor components subjected to the most extreme conditions are the (inner and outer) vertical targets, tungsten blocks (monoblocks) bonded to cooling water pipes. Mitsubishi Heavy Industries and Hitachi are responsible for the manufacturing of the outer vertical targets (OVT) for the ITER project. Allied Material, a member of the Sumitomo Electric Group, has developed a high-purity tungsten monoblock with excellent thermal shock resistance and is supplying it as a component for the ITER divertor. Yamato Alloy is also involved in the manufacturing of the divertor for the ITER project, while Metal Technology is responsible for the production of the divertor cassette for JT-60SA.

Beyond ITER, Helical Fusion, in collaboration with the National Institute for Fusion Science (NIFS), is pioneering an innovative liquid-metal blanket that integrates divertor functionality. This approach aims to enhance both heat resistance and cooling performance, offering a potential breakthrough in plasma exhaust heat management, which is one of the most critical challenges for next-generation fusion plants.[29]

4) Vacuum Vessel

The vacuum vessel contains the plasma in a sealed environment. Toshiba Energy Systems & Solutions is responsible for the manufacturing of the vacuum vessel for JT-60SA, and progress is being made on the construction of the fusion machine utilizing high-precision vacuum technology.[30] It should be noted that the vacuum vessel used in JT-60SA is different than the vacuum vessel for ITER.

The ITER vacuum vessel has a thicker structure with integrated radiation shielding capabilities. requiring full-perimeter, complete penetration welding and presenting distinct technical requirements. In addition, the engineering R&D carried out during the engineering design activities of ITER led to the production of a full-scale vacuum vessel sector model in 1997, and although different from the current ITER specifications, contributed to the development of vacuum vessels.[31]

5) Plasma Heating Device

The plasma must be heated in order to achieve fusion, and several plasma heating devices have been developed. One such device is the gyrotron, which heats plasma using high-frequency waves.

In producing heating devices for ITER, Canon Electron Tubes and Devices collaborates with the National Institutes for Quantum Science and Technology (QST) to develop and manufacture gyrotrons utilizing high-frequency electromagnetic wave technology. Tokyo Electron and JASTEC are responsible for the production and delivery of high-voltage power systems and superconducting magnets necessary for the operation of ITER's gyrotrons. Kyoto Fusioneering is promoting advanced development and industrial application of gyrotrons, and has successfully supplied organizations such as the UK Atomic Energy Authority (UKAEA) and Tokamak Energy (UK).

Another plasma heating device is known as the neutral beam injection (NBI) system. This technology heat plasma by injecting a high-speed beam of neutral particles into an experimental fusion device.[32]

QST is developing accelerators and high-voltage power supplies for ITER. These devices are developed and manufactured in collaboration with Hitachi. Hitachi is contributing to the development of plasma heating equipment for the ITER project by manufacturing key components for the 1 MV ultra-high voltage power supply test facility currently under construction in Italy. The technology will then be used in the production of the neutral particle beam injection device (NBI) intended for ITER. Hitachi has been engaged in the development and production of these devices for over 30 years, supplying NBIs to devices such as Heliotron-E, JT-60, and LHD. The neutral particle beam is considered one of the primary methods for heating and driving current in ITER and JT-60SA, with Japanese research institutions and industries being deeply involved in the development and supply of its core technologies.

6) Ancillary Technology and Control Systems

The operation of a fusion machine necessitates a variety of technologies, including cooling systems, neutron shields, and insulating materials. Companies that supply these parts include IHI (helium circulation pumps for superconducting coil cooling), Asahi Metal Industry (copper plating technology in cooling systems), Hazama Ando Corporation (neutron shielding materials), and Shoritsu Industry (insulating materials). These companies are develop and provide the foundational technologies that support the stable operation of fusion machines in their respective fields of expertise. Furthermore, NTT, in collaboration with QST, is developing AI-powered plasma control technology.[33]

(4) Plant Integration

The various technologies associated with fusion must be integrated into the fusion plant for them to be useful in generating power. It is then key to have an integrator that can seamlessly integrate and coordinate the various technological components used in the fusion plant.[34] Overseas, this role is being filled by private startups and state-owned enterprises, while domestically, it is trending towards fusion machine development startups that fulfill this function.

There is a possibility that integrators, as the central figures in development, will collaborate with component and material manufacturers of fusion machines to take control over plant development—a potential developing trend in the domestic and international fusion energy industries.

(5) Initiatives of Universities and Research Institutions[35]

Advancements are being made in a variety of research efforts towards the realization of fusion energy at universities and research institutions in Japan. QST is the central domestic organization promoting the ITER project and the Broader Approach (BA) activities. It is conducting plasma research by operating the tokamak-type superconducting plasma experimental device JT-60SA at the Naka Fusion Institute in Naka City, Ibaraki Prefecture. Safety tests for the test blanket module to be used in ITER is being conducted in Rokkasho Village, Aomori Prefecture.[36] The development of the IFMIF prototype accelerator (LIPAc) has completed its long-pulse beam acceleration test using a radio frequency quadrupole linear accelerator (RFQ) in June 2024, and is currently preparing for the final stage of testing for its superconducting accelerator.[37]

The National Institute for Fusion Science (NIFS), a core organization under the National Institutes of Natural Sciences, operates the Large Helical Device (LHD), one of the largest of its kind in the world. The NIFS conducts research in plasma physics and fusion technology, making progress in enhancing the confinement performance of ultra-high-temperature plasma, studying the interactions between plasma and wall materials, and developing technologies for extended operation.

With regard to university initiatives, the Institute of Laser Science at Osaka University is advancing research in laser fusion technology utilizing the Gekko XII large-scale laser experimental device. Laser fusion utilizes the inertial confinement method to achieve fast combustion by creating an environment with extremely high energy density.

Furthermore, many universities such as Tohoku University, the University of Tokyo, Nagoya University, Kyoto University, Kyushu University, and the Graduate University for Advanced Studies are actively engaged in research related to fusion energy. At these universities, studies on plasma control and fusion machine design using simulation technologies, as well as predictive modeling of plasma using AI are being conducted in addition to research on plasma physics and fusion materials. In particular, the University of Tokyo contributes to the ITER project with simulation research and studies on fusion machine blankets, while Kyoto University and Kyushu University are advancing developments in plasma theory and advanced measurement technology.

We can see that fusion energy research in Japan is being headed by national research institutes such as QST and NIFS, in collaboration with universities and international projects. There is an active commitment by the government to create advanced research facilities and train the next generation of researchers, accelerating efforts towards the establishment and practical application of fusion technology.

4. Current Status of Considerations Regarding the Safety Assurance of Fusion Energy Development in Japan

4.1 The Necessity of Rules and Development in Fusion Energy[38]

The performance and design of equipment required for the development of fusion energy are significantly influenced by the framework of safety regulations applied to them. To encourage participation by private enterprises that facilitate innovation and to advance industrialization and commercialization, it is crucial to establish safety regulations as early as possible. The Cabinet Office has formulated the Fusion Energy Innovation Strategy as a national strategy aimed at the industrialization of fusion energy.

Additionally, a task force has been established to deliberate fundamental safety assurance considerations towards the realization of the strategy. This task force, made up of technicians, regulatory experts, and industry representatives, cooperate with the government to establish basic approaches for ensuring safety while achieving fusion energy generation. These approaches were presented to and approved in March 2025 by the Fusion Strategy section of the Expert Council for Strengthening Innovation Policy Promotion after receiving and incorporating public feedback .

Fusion energy is inherently much safer than fission reactors. Reasons for this include the fact that fusion reactions cease once the fuel supply is cut off. Fusion energy also does not generate highly radioactive waste like in fission reactors, which must be disposed of underground. However, when constructing devices for industrialization and commercialization, it is essential to establish appropriate regulations from a safety assurance perspective. It is stated in the Basic Approach to Ensuring Safety for the Realization of Fusion Energy that regulation is based primarily on the following four points.

(1) Principles for Ensuring Safety

Since fusion devices generate radiation or contain radioactive materials such as tritium, it is necessary to implement safety measures based on the fundamental principles of radiation protection recommended by the International Commission on Radiological Protection (ICRP), namely “justification,” “optimization of protection,” and “application of dose limits”. When considering safety measures, it is considered effective to assess the impact on humans and the environment during both normal operation and accident conditions in future devices, and to reduce exposure doses as much as reasonably achievable (the ALARA principle: As low as reasonably achievable).

(2) Scientific and Rational Approach

A wide variety of technologies are involved in the design and implementation of devices. It is deemed appropriate to apply regulations according to the type of device and the associated risks (graded approach), accumulating the knowledge needed to steer these regulations during the research and development stage. Furthermore, it is also considered appropriate for regulatory authorities to respond flexibly and promptly, with consideration given to the status of the research and changing concerns of operators. Regulatory authorities should also work toward establishing transparent safety regulations while sharing safety-related information and demonstration data.

(3) Early Examination of the Framework for Ensuring Security

Current targets for the construction of pilot plants and prototype fusion machines are projected for the 2030s, so it is essential for operators to start discussing with regulatory authorities risk information sharing and safety measures from the early stages of equipment design. The US and other foreign countries have already started developing early-stage coordination systems, and there is a need in Japan to clarify regulatory procedures and strengthen collaboration with relevant organizations.

(4) Utilization of International Coordination Platforms

Within international frameworks such as the G7, IAEA, and the Agile Nations Working Group (WG),[g] discussions are underway among countries to harmonize approaches for ensuring safety and regulation. The joint recommendations by the Agile Nations Fusion Energy Working Group in October 2023, as well as the communique from the G7 Puglia Summit, explicitly state the “commitment to a consistent regulatory approach." It is also noted that the IAEA points out the benefits of cooperation among international regulatory authorities. Going forward, it will be necessary to actively utilize international cooperative frameworks to facilitate knowledge sharing and the design of coherent systems.

[g] Agile Nations: An intergovernmental regulatory cooperation network aimed at promoting collaboration among participating governments on innovative regulatory practices

4.2 Current Regulatory Framework for Nuclear Energy and Radiation

4.2.1 The Position of the Basic Act on Atomic Energy and Fusion Energy

Nuclear power generation and utilization of radiation in Japan are primarily governed by the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (hereinafter referred to as the “Reactor Regulation Act") or the Act on the Regulation of Radioisotopes and Related Matters (hereinafter referred to as the “RI Act”). There are differences in what is subject to regulation and the scope of application between fission reactors (nuclear power generation) and fusion machines.[39]

The Basic Act on Atomic Energy (Act No. 186 of 1955) (hereinafter referred to as the “Basic Act") sets forth the fundamental principles of Japan’s nuclear energy policy. It stipulates as its basic policy that the research, development and utilization of nuclear energy “shall be limited to peaceful purposes, aimed at ensuring safety, carried out independently under democratic management, the results shall be made public, and shall proactively contribute to international cooperation.” In Article 3, Item 1 of the same act, “nuclear energy" is defined as “all types of energy released from atomic nuclei during the process of nuclear transformation." This is interpreted to include not only fission reactions but also fusion reactions.

On the other hand, the tritium used in fusion devices is not a “nuclear fuel material" covered under Article 1 of the Ordinance on Definitions of Nuclear Fuel Material, Nuclear Source Material, Reactors, and Radiation (Cabinet Order No. 325 of 1957) pursuant to Item 2 of the Article 3 of the Basic Act. Additionally, under the Basic Act, a “reactor" is defined in Article 3, Item 4 of the same act as a “device that uses nuclear fuel material as fuel."

Thus, the tritium used in fusion devices is not defined as “nuclear fuel material," making fusion devices not “reactors" as defined by the Basic Act. Therefore, the current Reactor Regulation Act, which regulates the operation of reactors or the use of nuclear source materials and nuclear fuel materials under the Basic Act, does not apply to fusion devices as they are not defined as reactors, nuclear source materials, or nuclear fuel materials as stipulated in the Basic Act.

For example, JT-60SA, a tokamak-type superconducting plasma experimental device, and other similar devices are regulated as a “plasma generation device (using deuterium as fuel)," which is “a type of radiation generation device" based on the RI Act. But the current RI Act does not permit tritium to be used as a fuel, so amendments to the act would be required to allow tritium to be used as fuel in plasma generators.

4.2.2 Current Regulatory Framework

Nuclear power generation and the utilization of radiation in Japan are regulated by the following laws.

(1) The Reactor Regulation Act (Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material, and Reactors)

The regulations pertaining to the installation, operation, decommissioning, and other related activities of nuclear reactors are stipulated by the Reactor Regulation Act. This Act primarily targets reactors that utilize nuclear fission, and it applies to facilities that use nuclear fuel materials such as uranium and thorium.

Fusion devices use tritium, which is not classified as a “nuclear fuel material" and therefore are not subject to the regulations of the Reactor Regulation Act.

(2) Regulations on Radioactive Isotopes and Related Matters (RI Act)

The RI Act regulates the manufacture, use, disposal, and other related activities involving radioactive isotopes and radiation-generating devices. This act pertains to research institutions, medical devices, and industrial establishments that handle radioactive materials or radiation-emitting devices.

Fusion devices may also be regulated under the framework of the RI Act. For instance, at JT-60SA, experiments are conducted using deuterium-deuterium (D-D) fusion reactions. This process generates neutrons, X-rays, and tritium, and various secondary radioactive isotopes (RIs) are produced through the activation of structures and other materials. As a result, the equipment in question is classified as a “radiation-generating device" and is subject to regulation under the RI Act, necessitating the acquisition of a usage permit[h].

Also, in the notifications by the Science and Technology Agency, JT-60SA is classified as a “plasma generation device" within “radiation-generating devices." However, this classification is specified as “limited to those conducting nuclear reactions exclusively between deuterium and deuterium."[40] On the other hand, since there are also fusion machines that utilize the nuclear reaction between deuterium and tritium, it is not clearly stipulated in the current RI legal framework whether these devices are classified as “radiation-generating devices." In other words, under the current RI law, fusion devices that involve D-T reactions are not subject to regulation. Therefore, it is necessary to consider how to position and regulate fusion devices that use the D-T reaction.

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[h] Regarding the LHD, it is subject to the RI Act during D-D testing, and the Ionizing Regulations in plasma experiments that do not use D-D.

(3) Regulations for the Prevention of Ionizing Radiation Hazards (Ionizing Regulations)

The Ionizing Regulations, based on the Industrial Safety and Health Act, govern X-ray generators and low-energy accelerators, among other devices. This regulation primarily establishes safety measures to prevent worker radiation exposure, and may also apply to fusion devices. In particular, considering the impact of X-rays generated during the operation of fusion devices, it is essential to implement safety management measures for workers.

4.3 History of Safety Assurance Considerations in Fusion Energy Development

4.3.1 Discussions Regarding Fusion Energy Regulations in Japan Conducted Thus Far

Regarding the review of regulations related to fusion energy equipment thus far, there have been multiple rounds of legal discussions, starting in the 1980s, concerning fusion energy-related equipment such as JT-60, JT-60U, the Tritium Process Laboratory, fission chambers, and 1-MeV negative ion source test equipment.

Specifically, discussions were held on safety regulations for the following fusion devices.

JT-60, JT-60U, JT-60SA:

Operated as tokamak fusion experimental devices, with experiments using deuterium conducted at JT-60U. JT-60 is regulated under the Industrial Safety and Health Act, whereas JT-60U and subsequent models are regulated as “radiation-generating devices" under the RI Act.

Tritium Process Laboratory (TPL):

The facility handles a large quantity of tritium and is regulated under the RI Act.

Fission chamber:

This neutron detector contains uranium and is subject to regulation under the Reactor Regulation Act as a “small quantity of nuclear fuel material."

1-MeV negative ion source test facility:

The device accelerates hydrogen negative ions and only generates X-rays. However, it is subject to regulation under the RI Act due to its acceleration energy of 1 MeV or more.

In particular, during the ITER siting campaign (2000-2005), four documents were established as official texts in preparation for hosting a domestic site: “Basic Concepts for Ensuring the Safety of ITER Facilities" (Nuclear Reactor Regulation Division, Science and Technology Agency), “On Ensuring the Safety of ITER" (Nuclear Safety Commission), “On the Approach to ITER Safety Regulation" (Nuclear Safety Commission), and “On Ensuring the Safety of ITER" (ITER Safety Regulation Study Group, Ministry of Education, Culture, Sports, Science and Technology) (Figure 4-1).

The safety regulations for ITER in France were subject to the French Installation Nucléaire de Base (INB) regulations, applying safety regulations equivalent to those for nuclear reactors.

In 2023, an international working group (including the UK, Japan, and Canada) was established under the Agile Nations intergovernmental regulatory network. This working group was created to promote cooperation on innovative regulatory implementation measures and jointly announced recommendations on the regulatory framework for fusion energy. The recommendations include five suggestions on how to construct a regulatory framework for fusion energy facilities, supported by two case studies.

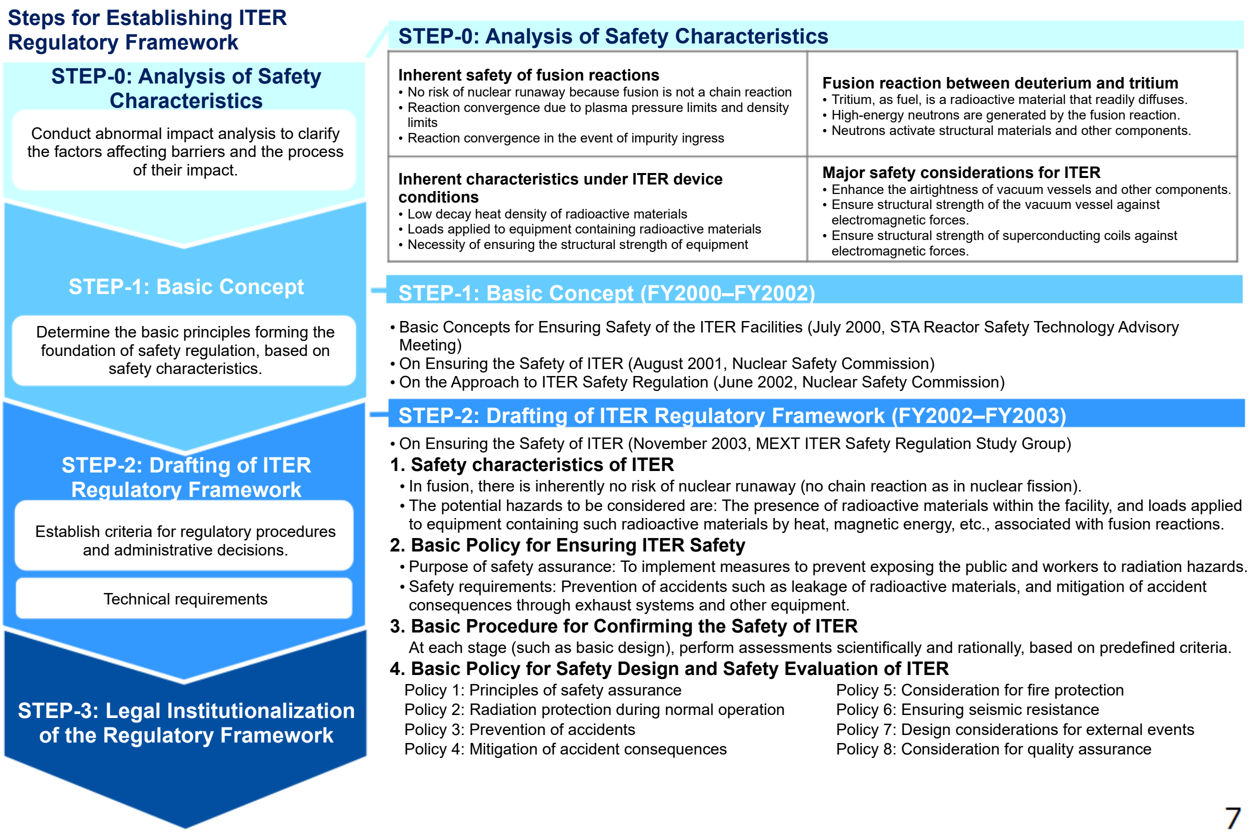


Figure 4-1 Past domestic considerations (regulatory discussions during the ITER siting campaign)[41]

4.3.2 On International Fusion Energy Regulations (from IAEA Fusion Key Elements)

The IAEA (International Atomic Energy Agency) has formulated the "Fusion Key Elements"[42] as a shared vision for fusion energy development, outlining the pathway from research and development to demonstration and commercialization.

The following provides a concise introduction to the "Fusion Key Elements" from the "Basic Approach to Ensuring Safety for the Realization of Fusion Energy (Draft Outline)" (January 28, 2025, Expert Panel on Fusion Strategy, Cabinet Office).[41]

In November 2024, the IAEA published the first edition of the Fusion Key Elements. This booklet has been created as a shared global vision for the development of fusion energy. This document outlines the pathway from research and development to demonstration and commercialization, with the aim of building a common understanding of fusion and indicating a collaborative framework that supports the maintenance and advancement of global initiatives. The target audience of the booklet includes researchers and engineers involved in fusion energy, regulatory authorities, entrepreneurs, stakeholders, and policymakers.
The Fusion Key Elements consists of the following six Key Elements, and, of these, "3. Safety, Security and Non-Proliferation" is related to regulation, as shown below.

1. Research, Development and Demonstration
2. Industrialization
3. Safety, Security and Non-Proliferation
4. Global Collaboration
5. Roles of Stakeholders
6. Public Engagement

Safety, Security and Non-Proliferation

Regulation of safety and security of fusion plants needs to be commensurate with their risks, taking into account their unique features, such as the absence of a chain reaction and their immediate shutdown capabilities. Equally important is ensuring low risk of proliferation by design and through regulatory oversight as fusion energy develops.

[Radiation Safety Fundamentals]

Safe, secure designs are essential for the successful deployment of fusion energy. The safety approach for fusion plants needs to be consistent with IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles, which applies to all circumstances that give rise to radiation risks, including uses in the medical field, power generation and industry applications. The fundamental objective within this framework is to protect people and the environment from harmful effects of ionizing radiation. The fundamental safety principles in SF-1 are applicable to all facilities and activities utilized for peaceful purposes, throughout their lifetime, and to protective actions to reduce existing radiation risks. Such facilities and activities include any place where radioactive materials are produced, processed, used, handled, stored or disposed of at such a scale that consideration of protection and safety is required. Therefore, these principles can apply to fusion plants, which both use and produce radioactive materials at a scale that warrants consideration of safety.

IAEA General Safety Requirements Parts 1–7 address topics such as safety assessment and regulatory frameworks. The General Safety Requirements are applicable to all uses of radiation, including fusion machines. The organizations responsible for assessing and controlling radiation risks need to assess and control radiation risks to people and the environment as a result of normal operations and incidents/accidents. This applies throughout the lifecycle of the facility, including design, operation, fuel and waste management, and dismantling/decommissioning. Modelling and diagnostics will be needed to support the safety case. It is essential to consider safety measures from the very beginning of the design process for all involved systems. Owing to the novelty of fusion plants, the uncertainties in the performance of various systems need to be carefully addressed in the safety analysis. Depending on the technology, different material interactions (e.g., lithium, water), radioisotopes and particle energies are expected, resulting in a variety of hazards that need to be considered. Fusion plant designers need to consider these principles to reduce hazards and minimize radioactive waste, where feasible.

[Approaches to Regulating Fusion Energy]

Fusion experiments have already been licensed and operated for research and development (R&D) in some IAEA Member States. In coming years, designers are expected to produce the first pilot and demonstration projects. If these projects are successful, they could be followed by widespread commercial adoption of fusion plants. For the designs being contemplated for widespread commercial adoption, Member States are currently evaluating approaches to regulating fusion plants that are commensurate with their risks. These evaluations take into account the inherent features of fusion (e.g., lack of chain reaction, immediate shutdown on loss of power), the characteristics of the radioactive materials involved and the management of radioactive materials on site. This approach is reflective of the IAEA's graded approach to regulations.

Requirements and guidance already exist or are being developed in Member States for fusion plants and the safe management of radioactive waste, consistent with national frameworks and the associated hazards. These requirements and guidance address both safety and security.

The IAEA can support regulatory bodies in developing safety requirements and security guidance for fusion energy that are appropriate for the technology and hazards and enable incorporation of lessons learned as designs mature, as has been done in other regulatory regimes. Cooperation among regulators is advantageous. Common approaches and consistent decision making across Member States, where feasible, will streamline the application process, as designers will have a lesser need to revise their applications, technical solutions and justifications across jurisdictions. Common terms and common positions on technical matters can aid all regulators, even if different regulatory approaches are applied. Continued regulatory collaboration on emerging technical challenges, as well as security topics such as cybersecurity, can help to share knowledge and experience so that fusion plant regulations address these areas appropriately.

International organizations such as the IAEA can facilitate bilateral and multilateral discussions among Member States developing similar regulatory frameworks. Coordination within the IAEA for consistency and coherence of effort will support all Member States in advancing their fusion regulatory structures. A decision on whether the IAEA needs to develop safety standards for fusion may not be warranted until fusion plants have matured.

Industry standards organizations could have a role in developing common design approaches that can help to streamline regulatory reviews.

[Transition to Widespread Commercialization of Fusion Plants]

To date, experience in fusion energy has been limited to R&D projects. Fusion energy production and commercialization are expected in the future. This will involve construction of fusion plants (prototype, demonstration and/or commercial plants).

As fusion technology develops further, regulatory bodies may adopt processes that are appropriate to the stage of development. For example, the graded approach might be used to specify different licensing requirements and oversight at each stage. Differences driving safety decision making can include higher inventories of radioactive materials; transportation, storage and processing of fuel; waste disposal categories and volumes; and the need for active cooling of some components. Regulators are likely to find that their reviews and processes become more efficient for n-th of a kind plant. Specifically, new licensing paradigms might be needed for mass manufacturing and widespread deployment on a rapid timescale.

[Other Hazard Considerations]

The IAEA and many Member State regulators coordinating fusion energy projects focus on radiological safety and security. Fusion plants have additional potential hazards of an industrial and occupational nature, given the high energy in the system and potentially toxic materials. A detailed discussion of these hazards is outside the scope of this publication. However, in communicating with the public, the fusion energy community can discuss how to identify and mitigate these hazards to protect workers and the public.

[Non-Proliferation Considerations]

It is important for designers to be mindful of prevailing nuclear export control regimes regarding materials associated with fusion energy, such as tritium and lithium-6, and certain technologies, such as analysis codes. For fusion designs that do not process, use or produce nuclear material, the IAEA does not currently apply any safeguards measures other than those needed to resolve questions, where applicable, relating to the accuracy and completeness of the information provided by Member States. Existing international safeguards agreements apply to designs that process, use or produce nuclear material. As more information about fusion plant designs becomes available, further consideration is required to ascertain whether the scope of IAEA safeguards would apply more broadly to fusion plants.

4.3.3 Progress in Reviewing the Regulations for Current Fusion Energy

Considerations for ensuring the safety of existing fusion devices have been conducted within the framework of existing legal systems. However, the challenge ahead lies in establishing a new framework for ensuring safety with a view to realizing commercial fusion plants.

The following is an excerpt from the “Basic Approach to Ensuring Safety for the Realization of Fusion Energy” (as decided by the Expert Panel on the Fusion Energy Strategy, Cabinet Office, on March 25, 2025).[43] The Basic Approach to Ensuring Safety was formulated as a guideline for discussions on safety regulations for fusion devices, identifying issues to be examined in the future.

Issues to be Examined in the Future

*To be examined taking into account future technological developments and international trends.

*It is necessary to ensure information sharing and transparency in discussions, and to gain acceptance from society.

1) Legal Framework

- Businesses involved in advancing research and development must sort out which items should be regulated to ensure safety once the concepts of fusion devices and safety risks to be considered have been identified to a certain extent. Sufficient thought must be put into regulation with the characteristics of fusion devices in mind.
- In examining regulation, it is necessary, in addition to recognizing differences in regulations and procedures under current legislation, to carefully set out the applicable legal framework, taking into account the requirements specific to the regulation of fusion devices.
- Pilot plants,* which may include prototype fusion machines and commercial start-ups, may not be the only things capable of sustaining a fusion reaction in the future, it will be necessary in due course to reconsider the structure of the regulatory legal framework.
- However, if a new fusion device were to be built before the aforementioned reviews are done, it is considered appropriate to temporarily have the device regulated under the current RI Act if the risks are comparable to those of existing fusion devices, within the scope of the equipment requirements covered by the RI Act. In such cases, the application of regulations should be considered with due regard to the diversity of device types and technologies, so the same risks do not apply to different fusion devices.

2) Arrangements for Examining the Safety-Assurance Framework

- In considering scientific and rational regulation of fusion devices, it is essential to strengthen the regulatory authority and other government bodies while taking into account technological advances and international developments.
- While maintaining a separation between promotion and regulation, there must also be forums for continuous information sharing and dialogue between the government, project proponents, and other parties. Mechanisms should be established to encourage active collaboration between the government and relevant stakeholders such as project proponents.
- Appropriate information sharing not only with stakeholders but also with the public at large is required to ensure transparency of the discussions and to secure acceptance from society.

3) Accumulation of Knowledge

- In assuring the safety of fusion devices in the future, it is necessary—beyond the discussions held at the time of the ITER siting campaign—to promote the collection of safety-related knowledge and research by both developers and the regulatory authority. This should be done even at the research and development stage so that new insights can be acquired.
- Risks and hazards associated with tritium, material activation, radioactive waste, and other elements, should be continuously examined, with more research conducted on safety.
- It is important to establish, at an early stage, risk assessment methodologies that reflect discussions in relevant academic societies and international developments.

4) Security and Non-Proliferation

- According to the IAEA Fusion Key Elements, regulation of safety and security for fusion devices (which are inherently safe and can be shut down immediately as there is no chain reaction) must be commensurate with the level of risk.
- As discussions progress, emphasis should be placed on reducing the risk of radioactive material contamination through system design and developments in regulations.
- Efforts relating to security and non-proliferation of fusion devices should likewise be examined, taking into account the future need for timely responses and other measures.

5. General Overview of Security Trade Control for Fusion Energy-Related Technologies

5.1 The Current State of Security Trade Control for Fusion Energy-Related Technologies

5.1.1 Japan's Security Trade Control

The Security Trade Control Regulations is a regulatory framework in Japan that requires prior approval from the Minister of Economy, Trade and Industry when providing regulated technology or exporting goods under the Foreign Exchange and Foreign Trade Act (FEFTA). These regulations are designed to prevent the transfer of weapons or goods and technologies (including software) that can be converted for military use to entities of national security concern. The FEFTA implemented in Japan is based on international agreements, and the handling of specific goods and technologies is strictly controlled through list controls and catch-all controls. (Figure 5-1). Companies engaged in exporting are required to comply with these regulations and to appropriately determine which of their items are regulated and manage how they are exported.

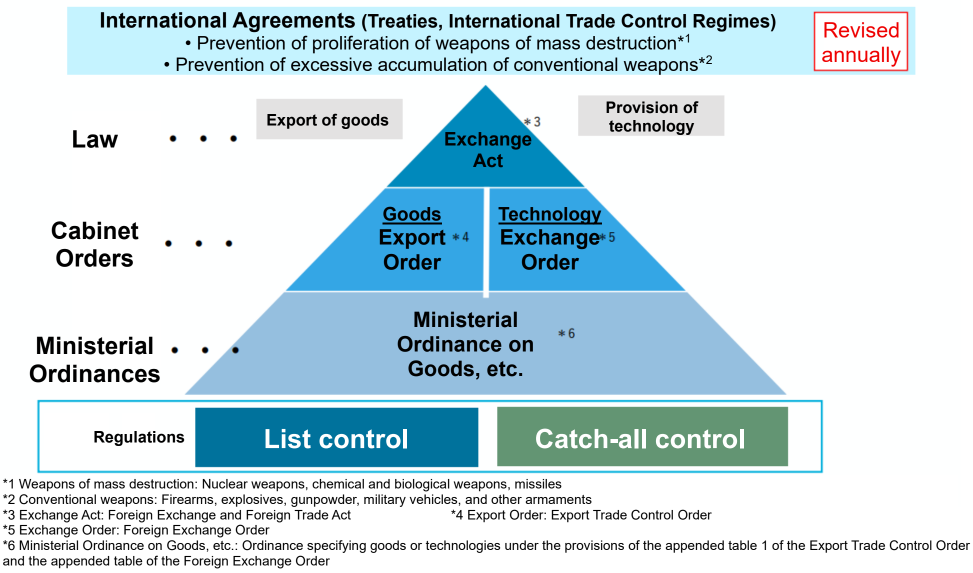


Figure 5-1 Overview of Japan's Security Trade Control Regulations[44]

List controls:

List controls detail weapons and items that are highly likely to be used in activities such as the development of weapons of mass destruction and conventional weapons, and are listed in laws and regulations based on international agreements. Permission from the Minister of

Economy, Trade and Industry is required when exporting or providing goods and technologies on this list.[45]

Catch-all controls:

Catch-all controls apply to items that have a risk of being used in activities such as the development of weapons of mass destruction or conventional weapons, even if they are not subject to list controls. Permission from the Minister of Economy, Trade and Industry is required when exporting or providing goods and technologies subject to catch-all controls.

5.1.2 Achieving Appropriate Security Trade Control

In the “Security Trade Control Guidelines [Introductory Edition]" by the Ministry of Economy, Trade and Industry (METI), it is stipulated that the roles company departments related to (or persons in charge of) export control should be defined according to what the company is, such as business type, company size, and number of employees.[45] This means companies and other entities working with fusion energy need to establish an appropriate framework in accordance with their scale and the products or technologies they handle. Most importantly, individuals involved in exports—whether in legal affairs, engineering, or sales—must understand and take ownership of security trade control responsibilities.

Companies are to refer to the latest version of the METI-published matrix table to determine if the fusion energy-related goods and technologies they are providing are subject to current list controls (classification).[46] Guidelines should also be consulted when necessary, such as those published by the Center for Information on Security Trade Control (CISTEC). It is essential to bear in mind that, even if goods or technologies were developed for the utilization of fusion energy, regulatory scrutiny may be levied to things that can be repurposed for weapons of mass destruction or conventional weapons.

Security trade control is a regulatory system designed to ensure that advanced goods and technologies are properly managed to prevent their diversion to weapons of mass destruction or conventional weapons. Companies involved in fusion energy must appropriately understand the significance of security trade control and rigorously implement such controls.

5.2 Corporate Practices in Exporting Fusion Energy-Related Technologies

5.2.1 Security Trade Controls of Company A (Based on an Interview with the Company)

(1) System and Practices for Security Trade Control

J-Fusion has an export control department, an Export Control Committee with representatives selected from various technical departments related to export control, and appointed key personnel for export control in each department as part of its internal security trade control framework. Externally, the company participates in CISTEC committees and cooperates in revising guidelines.

As for the security trade control measures under this framework, J-Fusion has created procedures for transaction screening and classification. These procedures are conducted in scalable units for effective technology transfer control. In high-risk areas, classification is conducted in finer units to avoid omissions. In areas deemed lower risk, classification may be performed for an entire set of technologies with similar design, manufacture, or intended use. Additional measures include: establishing internal rules; conducting internal audits; applying for and renewing export licenses with METI; providing regular training; sharing “near-miss” cases; and having staff take and obtain certification in the Security Trade Control (STC) Examination (administered by CISTEC).

(2) Points to Note in Implementing Security Trade Control

When engaging in business with companies outside Japan, it is also necessary to comply with the security trade control regulations of the trade partner’s country. For example, under the US Export Administration Regulations (EAR), certain items are subject to control not only when exporting from the US to other countries, but also for reexports from a third country such as Japan.[47] Companies must check the trade requirements each country’s trade requirements and, when necessary, establish appropriate export control systems (including staffing and licensing). In some cases, beyond legal requirements, companies may need to engage in voluntary internal controls such as teaming arrangements to align with partner requirements.

If the technical documents of an invitation to tender (ITT) in an overseas bid includes controlled technologies, it is often necessary to submit an end user certificate and obtain an export license from the customer’s national regulatory authority before the documents can be received. This process may take a considerable amount of time. Sufficient time should be secured for obtaining an expert license from METI when sharing or submitting technical proposals containing controlled technologies to companies located overseas (including overseas subsidiaries of a company group).

Export licenses for items subject to list controls can be applied for individually or in bulk. An individual license application is for specific, individual contracts. A bulk license application allows the exporter to obtain a license for items within a defined scope. This eliminates the need to apply for a license for every contract, but requires the exporter to have an internal export control system capable of classifying and screening its items.[45] A bulk license can improve efficiency when a specific category of items needs to be exported multiple times to a specific destination. However, bulk licenses have a limited scope in what can be exported and the destinations, so advance confirmation is necessary.

5.2.2 Security Trade Controls of Company B (Based on an Interview with the Company)

(1) System and Practices for Security Trade Control

Company B has developed a "Security Trade Control Program" in accordance with applicable laws, prepared internal regulations or other guidelines within relevant departments, and operates under that program. The program is reviewed and subject to periodic inspections by METI. The company's security trade control structure designates: A classification control officer for each section; an export control officer for each department; and a final export operations officer for each division. In addition, the legal department assigns personnel to handle export control, including system management and licensing procedures.

To enhance security trade control, Company B provides in-house training two to three times a year, both online and in person, covering basic aspects of security trade control, practical procedures, and case studies using examples from the US. Internal audits are conducted every two to three years to review export control procedures.

(2) Points to Note in Implementing Security Trade Control

Export restrictions and prohibitions on nuclear proliferation or military use must be cleared with the country receiving the goods. Both Japanese domestic laws and the laws of the importing country must be thoroughly reviewed, with sufficient time and personnel allocated so the final export license can be obtained with no issue.

Company B currently only produces and exports a limited quantity of deuterium, so classification is relatively straightforward for them: items can be identified as "equipment for the production of deuterium and deuterium compounds" under the domestic list controls. However, if the company's fusion energy-related business expands in the future, export quantities of certain materials may exceed specified thresholds and require METI licensing. Therefore, Company B should exercise caution when planning large-scale projects involving exports.

It is standard practice to determine which government ministry has jurisdiction over production licensing for materials such as deuterium, tritium, or lithium-6 when a business conducts a development project involving exports. The permissible production quantities should also be checked. However, many fusion energy-related technologies are still in development, so there is significant uncertainty between the theoretical consumption values assumed for the export destination and the actual quantities required in operational plants. Therefore, actual usage should be thoroughly investigated and calculated, with production and export volume fluctuations taken into account when planning processes such as production and licensing applications.

This makes bulk license applications unfeasible because export quantities and concentrations vary by project, meaning projects should be managed under the assumption that individual licenses will be applied for.

Furthermore, it is projected there will be a global shortage of fusion energy materials in the future. National policy should be followed, and imbalances caused by competitive procurement should be avoided when conducting commercial-scale production and export.

6. Status of Fusion Energy Development, Regulation, and International Cooperation in Highly-Developed Countries

6.1 US Trends in Fusion Energy Regulation

6.1.1 Past Regulation of Fusion Energy in the US

The US Atomic Energy Act of 1954 authorized the US Atomic Energy Commission (AEC, now the US Nuclear Regulatory Commission, NRC) to regulate the handling of the following three categories of radioactive materials for the commercialization of nuclear fission energy:

- Special Nuclear Material (SNM):
  Includes plutonium, uranium-233, and uranium-235-enriched materials. When enriched, these materials can be used as explosive substances in nuclear weapons.[48] Fusion facilities do not manufacture or use SNM.
- Source Material:
  Includes thorium or uranium not enriched above natural isotopic abundance.[49] In fission facilities, these are essential to the production of SNM.[50]
- Byproduct Material:
  Non-SNM radioactive material made radioactive or produced during the production or use of SNM. This includes material generated when processing source material such as uranium or thorium.

The Energy Policy Act of 2005 (EPAct) expanded the regulation of byproduct material to include radioactive material produced by particle accelerators used for commercial, medical, or research purposes.[51] Some future fusion facilities may require tritium—classified as byproduct material and sourced externally—to initiate the fusion reaction. However, once operational, the facility can produce its own tritium, so the need for externally sourced tritium would diminish to zero over time.

As the US does not have explicit regulations for fusion devices, existing fusion devices have been treated as a type of particle accelerator that produces byproduct material and regulated under "General Domestic Licensing of Byproduct Material" (Title 10, Code of Federal Regulations, Part 30, or 10 CFR Part 30). This implies that regulation of byproduct material—originally intended for the radioactive products of nuclear fuel use or reprocessing under the 1954 Atomic Energy Act—was extended to accelerators by the Energy Policy Act of 2005 (EPAct), and further applied to the radioactive byproducts of fusion machines (the byproduct approach).

In actuality, the definitions of "particle accelerator" in the 2005 Energy Policy Act and in 10 CFR Part 30 both encompass characteristics of fusion machines:

- Definition in the Energy Policy Act of 2005:
  "A particle accelerator is a device that imparts kinetic energy to subatomic particles by increasing their speed through electromagnetic interactions."
- Definition in 10 CFR Part 30:
  "Particle accelerator means any machine capable of accelerating electrons, protons, deuterons, or other charged particles in a vacuum and of discharging the resultant particulate or other radiation into a medium at energies usually in excess of 1 MeV."

The US recognizes the need to evaluate how effectively the byproduct material-based approach can regulate fusion devices from a radiation protection standpoint, and develop future regulatory methods accordingly. The Nuclear Energy Innovation and Modernization Act (NEIMA), enacted in 2019, directs the NRC to establish a technology-inclusive regulatory framework that is compatible with the regulation of commercial advanced fusion plants by the end of 2027.[52]

In a staff memorandum to the NRC Commissioners dated April 20, 2009 (hereinafter referred to as the "NRC Staff Memorandum"), it was noted that treating fusion devices as "utilization facilities" could allow the Commission to exercise regulatory jurisdiction over such devices. Facilities classified as utilization facilities are subject to some existing reactor regulations. However, these regulations were designed for reactors handling fission energy and may be unduly stringent if applied without modification to fusion facilities, which generally present comparatively lower risks of radioactive material dispersion and contamination.

The NRC Staff Memorandum states that in order to treat fusion facilities as utilization facilities, it must be determined that: (1) fusion energy is included in the definition of "atomic energy" under the US Atomic Energy Act (AEA), or (2) the fusion reaction process is important to the Nation's defense and security, or could have a significant impact on public health and safety.

Regarding item (2), fusion devices are not currently considered important to national defense and security, and their impact on public health and safety remains within the scope of existing regulations covering radioactive materials and byproduct materials.

As for item (1), since the AEA defines atomic energy as "all forms of energy released in the course of nuclear fission or nuclear transformation," fusion can be considered to fall within the AEA definition of atomic energy. Historically, the US Congress has understood "nuclear transformation" to encompass fusion reactions.[53]

Congress has also interpreted the AEC (currently NRC) definition of "special nuclear material" broadly enough to allow for the future inclusion of substances used in fusion energy. However, at present, no materials usable in fusion power generation are classified as special nuclear material.

- The NRC's Definition of Special Nuclear Material (Updated February 19, 2019)
  Special nuclear material includes "any other material which the Commission determines to be special nuclear material." However, to date, the NRC has not declared any materials other than plutonium and uranium to be a special nuclear material.

Given that a wide range of substances—such as boron, hydrogen, tritium, and deuterium—are under study for potential commercial use in the fusion process, future classification of any substance used in fusion energy as a special nuclear material would require the NRC to conduct a comprehensive survey of all relevant substances.

Accordingly, the NRC may in the future exercise jurisdiction over commercial fusion devices as utilization facilities under the AEA only. This may occur if fusion devices come to use or produce energy of sufficient magnitude to be considered important to national defense and security or to have a significant impact on public health and safety.[54]

That said, applying the same standards to fusion facilities as to fission reactors could impose costly regulatory requirements aimed at mitigating risks that do not exist for fusion facilities.

6.1.2 US Policy Directions for Fusion Energy Regulation

The NRC has considered three potential regulatory approaches applicable to fusion devices[55]:

1. Utilization Facility Approach
   This approach would regulate fusion devices and facilities under existing reactor-related rules, such as: Domestic Licensing of Production and Utilization Facilities (10 CFR Part 50), Licenses, Certifications, and Approvals for Nuclear Power Plants (10 CFR Part 52), and the proposed Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors (10 CFR Part 53, under development). This approach could result in overly burdensome regulation for fusion devices, as their risks are more limited in terms of radioactive material dispersion, contamination, and long-term waste management compared to fission reactors.

2. Byproduct Approach
   This approach would regulate fusion devices through their byproduct material, applicable to General Domestic Licensing of Byproduct Material (10 CFR Part 30). Since fusion devices are not explicitly defined in current regulations, adopting this approach would require a review of the legal definition of "byproduct material" and possible revision of relevant regulations.

3. Hybrid Approach
   This approach would combine the above-mentioned utilization facility approach and byproduct approach—applying the byproduct approach up to a certain threshold, and

the utilization facility approach above that threshold. Careful analysis would be needed to determine the appropriate threshold limits for the byproduct approach.

Initially, both the Advisory Committee on Reactor Safeguards (ACRS) and the US Nuclear Regulatory Commission (NRC) considered recommending the hybrid approach. However, in April 2023, the NRC Commissioners unanimously adopted the byproduct approach.[56]

Since then, the NRC has been developing a regulatory framework for fusion power systems based on the byproduct approach. In December 2024, it published an outline of the regulatory framework for US fusion devices.

The proposed framework for US fusion devices aligns, to the extent practicable, with the existing requirements of 10 CFR Part 30 (the byproduct approach). It considers the designs of various fusion devices, and is grounded in the safety objectives and outcomes to be achieved, with due consideration of the associated risks.

The proposal calls for revisions to definitions and requirements for byproduct material management and inspection, waste disposal, and environmental impact assessment in licensing applications for fusion devices.

It also proposes amending the NRC's definition of "byproduct material" to reflect the definition contained in the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act (ADVANCE Act). The proposed amendment aims to incorporate the ADVANCE Act's definition of "fusion device," described in the following section, into 10 CFR Parts 20 and 30. It also proposes corresponding revisions to other regulations, thereby clearly distinguishing fusion devices from other particle accelerators for regulatory purposes. In addition, the NRC staff has prepared draft regulatory guides to accompany the proposed rules.

The outline of the fusion device regulatory framework is open for a 90-day public comment period, with the final rule scheduled for publication in October 2026 and implementation by the end of 2027.

6.1.3 Legal Definition of Fusion Device in the US

The Fusion Energy Act, which provides a statutory definition of what a fusion device is, passed the US House of Representatives on February 29, 2024, as part of the Atomic Energy Advancement Act. It was later amended to the ADVANCE Act during committee deliberations. The ADVANCE Act passed the House on May 8, 2024, and the Senate on June 18, 2024, as part of the Fire Grants and Safety Act.[57] As a result, the Atomic Energy Act of 1954 was amended to add the following definition of a fusion device as a type of particle accelerator:

- Definition of Fusion Device (Fusion Machine) Added to the Atomic Energy Act of 1954
  The term fusion machine means a machine that is capable of—(1) transforming atomic nuclei, through fusion processes, into different elements, isotopes, or other particles; and (2) directly capturing and using the resultant products, including particles, heat, or other electromagnetic radiation.

In other developments within the US, Massachusetts enacted legislation in 2022 to include fusion energy in the definitions of “clean energy” and “clean energy research.”[58] The state also passed legislation in 2023 to include fusion energy in its Renewable Energy Portfolio Standard.[59] In October 2023, California enacted legislation to distinguish fusion energy from nuclear fission under state law.[60] In the same month, North Carolina enacted The Promote Clean Energy Bill, which added the definition of clean energy to include nuclear energy, encompassing fusion energy[61]. Furthermore, in March 2025, Virginia amended its definition of clean energy to include fusion energy.[62]

[Article] On Commonwealth Fusion Systems’ Involvement in Regulatory Development

The regulatory discussion in the US began when the US Department of Energy (DOE) and the US Nuclear Regulatory Commission (NRC) identified the need to determine how new fusion technologies should be regulated. Commonwealth Fusion Systems (CFS) participated in these discussions from the outset as an industry stakeholder, contributing to the examination of possible regulatory approaches.

At the NRC’s initial meeting, NRC members had no clear view on how fusion technology should be regulated, so the first step was to determine an overall regulatory policy. At this stage, it was critical for industry to have a rational proposal coupled with a consistent position. Equally important was obtaining the NRC’s understanding that applying the same regulatory framework used for nuclear fission technology to low-risk fusion energy would be inappropriate—an achievement that significantly contributed to the subsequent growth of the fusion energy sector.

In developing the regulatory framework, the aforementioned parties worked in cooperation with private companies. They analyzed existing, well-established regulatory systems worldwide and the risk characteristics of fusion devices, reviewing virtually all possible regulatory options to identify the most suitable framework for fusion devices. Ultimately, it was concluded that the optimal approach would be to base the framework on particle accelerator regulations, and structure the framework in a way that allows for modifications and additions as needed.

The members also recognized the importance of considering device-specific characteristics in regulatory design. For example, the nuclear fission reactor-based standards applied to ITER did not take into account the private fusion sector or the types of devices under construction, resulting in prolonged legislative processes; in this respect, the UK and the US have advanced more quickly in establishing legal frameworks for fusion devices.

Standards specifically catered to the SPARC (a tokamak fusion device under development by CFS) are being created for the device's construction. Because fusion devices integrate existing industrial technologies—including electrical systems, energy storage systems, mechanical systems, cryogenics from the medical and aerospace sectors, toxic gas management systems, and radiation protection systems—experts from these fields have been engaged to share their knowledge in safe and reliable system design. With this knowledge as a foundation, efforts are being made to build a standards framework that emphasizes safety and reliability.

A “code of record” was created to identify the applicable regulations based on prior work and standards. Based on this code, in collaboration with the regulatory authorities, rules and standards were established for tokamak fusion devices covering equipment requirements (structural standards, civil engineering standards, and pressure vessel standards), electrical requirements (general electrical standards and energy storage standards), control requirements (cybersecurity standards and industrial control standards), and environmental requirements (pollution standards and radiological occupational safety standards). Referring to this code of record in future projects will enable smooth compliance with relevant rules and standards.

There are two important considerations when developing regulations for fusion devices.

First, as noted above, regulations for fusion devices should not be created simply by adapting the existing rules and standards for nuclear facilities and then revising them later. Building a regulatory framework for fusion devices on the basis of nuclear facility regulations would require reviewing approximately 40,000 potentially applicable rules and standards in the US, and the process would be similarly complex in Japan. Therefore, it is preferable to start from a clean slate to establish codes and standards that are appropriate to the technology and its associated risks, and to supplement and evolve them as necessary.

Second, it is essential to ensure that work-related regulations and standards do not impede the development of fusion energy. Some developers believe that complete regulations and standards must be in place before design and construction can begin; this is not the case in practice. Historically, the first nuclear power plants began operating in the early 1950s, but the American Society of Mechanical Engineers (ASME) did not publish its first nuclear power-related standard until 1963, resulting in an approximately ten year gap from when nuclear power plants came into operation and the appearance of the first standards. During that time, US industry built and operated nuclear facilities without fully developed codes and standards, instead modifying ASME Section VIII and introducing new rules and standards as needed. Accordingly, regulations and standards should not be imposed in a way that restricts development at a stage when the technology itself has not yet fully matured.

CFS's clear and rational roadmap to regulatory authorities from the industry side was a highly significant event. For Japan as well, it is critically important for domestic industry associations to present a consistent position in regulatory discussion to regulatory authorities and to approach regulatory considerations from a holistic perspective.

6.2 UK Regulatory Trends in Fusion Energy

6.2.1 Past Regulation of Fusion Energy in the UK

As in the US, the UK does not have regulations explicitly covering fusion machines. Instead, existing regulations applicable to radioactive materials and radiation-generating devices were applied to fusion devices.

The relevant regulatory authorities are the Environment Agency (EA) and the Health and Safety Executive (HSE). Under the 1971 Nuclear Installations Regulations, a “nuclear installation” is defined as a nuclear reactor based on nuclear fission. Therefore, the Office for Nuclear Regulation (ONR), which regulates fission facilities, does not have jurisdiction over fusion facilities.

At present, fusion facilities are regulated under the EA’s Environmental Permitting Regulations and the HSE’s legislation and regulations such as the Health and Safety at Work etc. Act, the Control of Artificial Optical Radiation at Work Regulations, the Control of Electromagnetic Fields at Work Regulations, the Ionising Radiations Regulations, and the Radiation (Emergency Preparedness and Public Information) Regulations.

6.2.2 UK Policy Directions for Fusion Energy Regulation

The UK government aims to begin supplying power from fusion energy in the early 2040s under the national Spherical Tokamak for Energy Production (STEP) program. Based on this program, the Regulatory Horizons Council (RHC)—the UK’s advisory body on regulatory reform—published a Report on Fusion Energy in June 2021. The report examined three regulatory options for fusion energy:

- Option A:
  Evolution and continuation of the current regulatory approach with HSE regulating on safety and EA on Environment
- Option B:
  Adaptation to ONR regulating safety (with EA still regulating on Environment)
- Option C:
  A new fusion-specific approach by a new regulator

The RHC, in its report, particularly recommended Option A among the three options above.

6.2.3 Legal Definition of Fusion Facilities in the UK

In October 2010, the Department for Business, Energy & Industrial Strategy (BEIS) published "Towards Fusion Energy: The UK Government's Proposals for a Regulatory Framework for Fusion Energy," initiating a two-month public consultation. Key issues on which views were sought included: (i) Occupational and public health and safety, (ii) Environmental protection and planning consent, (iii) Third-party liability, and (iv) Security of radioactive materials and safeguards.

Later in June 2022, the UK government issued "Towards Fusion Energy: Government Response," confirming that the future regulatory policy for fusion facilities—whether publicly or privately led—would follow Option A (EA and HSE as the principal regulatory authorities), with other agencies delegated authority to respond as necessary. It also announced plans to amend the law, via the Energy Security Bill, to exclude fusion facilities from nuclear regulation and licensing requirements under the Nuclear Installations Act 1965 (NIA65).

Additionally, in October 2023, the release of "Towards Fusion Energy 2023: Next Steps for the UK Fusion Strategy" coincided with the enactment of the Energy Act 2023, making the UK the first country in the world to introduce regulations explicitly addressing fusion energy.[56]

6.3 Regulation of ITER in France

In France, where ITER is located, there is no regulatory framework explicitly covering fusion facilities. However, such facilities must comply with EU directives, domestic French laws, decrees (décrets), ministerial orders (arrêtés), technical regulatory decisions, and individual decisions (resolutions) issued by the Autorité de Sûreté Nucléaire (ASN). Under domestic French law, fusion facilities fall under frameworks such as the Labour Code, the Public Health Code, and the Environmental Code.

Article L.593-2 of the Environmental Code, "Provisions Governing Basic Nuclear Installations (installations nucléaires de base, INB)," defines "basic nuclear installations" to include reactors using nuclear fission, fuel cycle facilities, storage facilities, accelerators, and facilities using large quantities of radioactive nuclides. Thus, the INB classification is based not on if the material is fissile, but on the quantity and radioactivity of the nuclides used.

For tritium, any facility authorized to hold more than 27 g must obtain INB licensing. ITER, authorized to hold up to 4 kg of tritium, was therefore licensed as an INB. This means that the same regulatory requirements applicable to fission facilities are also applied to fusion energy facilities. This is similar to the utilization facility approach seen in the US or to the Japanese application of the Reactor Regulation Act. ITER's INB license led to approval for construction in November 2012, placing it under French Nuclear Safety Authority (Autorité de sûreté nucléaire, ASN) jurisdiction.[56] However, this approach is highly conservative for fusion facilities, as it is designed for fission facilities. As a result, the regulatory compliance requirements during subsequent construction are considered one of the factors leading to increased construction costs for ITER and delays in the construction schedule.

It should be noted that the application of a regulatory approach equivalent to the utilization facility approach to ITER was due to the fact that, at the time of the ITER construction plan, there was still insufficient recognition of the differences in risk between fusion energy facilities and fission facilities. Consequently, when evaluating and approving the ITER project, it was deemed necessary to conservatively apply existing regulations for fission facilities. Today, as discussions on the potential differences in risk between fusion energy facilities and fission facilities have progressed, it has become important—and is widely regarded as desirable—to establish a safety framework that reflects those differences and does not hinder the development and deployment of fusion energy facilities.

6.4 Trends in Overseas Private-Sector Development

6.4.1 Commonwealth Fusion Systems (CFS)

CFS is a private company based in Massachusetts, US. As of March 2025, it is the fusion energy start-up that has raised the largest amount of external funding. Investors include the Massachusetts Institute of Technology (MIT), Bill Gates, Google, and others, with total funding exceeding USD 2 billion.

A spin-out from MIT, CFS builds on decades of research into high-field tokamak fusion experimental devices and its groundbreaking work on high-temperature superconducting (HTS) magnets to develop an experimental device that could potentially cost less than ITER. The company also seeks to ensure the scientific validity of its work by submitting all of its research results to peer-reviewed journals.

CFS is currently constructing SPARC, a tokamak plasma demonstration plant, with the goal of producing first plasma in 2026 and demonstrating critical plasma—where plasma output exceeds heating input—by 2027. Looking ahead, it aims to build a 400 MW ARC power plant in the early 2030s and has announced a collaboration with Virginia-based utility Dominion Energy on technical expertise and site-lease rights for its first ARC unit.

In February 2025, CFS announced a licensing agreement granting fellow fusion start-up Type One Energy the right to use its HTS cable technology. In this way, CFS is expected to lead the global fusion energy industry not only as a fusion machine developer, but also as a designer and manufacturer of HTS magnets for fusion applications.

6.4.2 TAE Technologies (TAE)

TAE, a private company based in California, US, is the second-largest fusion energy start-up globally in terms of external funding as of March 2025. Investors include Google, Chevron, and Sumitomo Corporation of Americas, with total funding exceeding USD 1.2 billion.

TAE is developing a field-reversed configuration (FRC) fusion device, ultimately aiming to achieve aneutronic hydrogen-boron-11 fusion. In 2022, Norman, TAE's fifth-generation fusion machine, achieved a plasma temperature of 75 million degrees Celsius.

The company is now working on Copernicus, its sixth-generation fusion machine, with plans to demonstrate D-T fusion feasibility in the mid-2020s. Subsequently, in the early 2030s, TAE plans to realize hydrogen-boron-11 fusion with its seventh-generation Da Vinci fusion machine, aiming for 350–500 MW power generation and grid supply.

6.4.3 Other Private-Sector Start-Ups

Canadian start-up General Fusion is developing a magnetized target fusion (MTF) fusion machine and, with support from the Canadian government, has been building a demonstration plant at Culham, UK, since 2021. Investors include the Canadian government's investment fund, Jeff Bezos (Amazon), and Tobias Lütke (Shopify), with total funding exceeding USD 400 million. The company aims to achieve critical plasma by 2026 and 230 MW power generation in the early 2030s.

US-based Helion is developing an FRC fusion machine, raising more than USD 600 million from investors including Sam Altman (OpenAI). In September 2023, Helion announced a joint plan with Nucor, the largest steel producer in the US, to develop a 500 MW fusion power plant. The company aims to operate a fusion machine with over 500 MW capacity by 2028 and has already signed an agreement to supply electricity to Microsoft.

UK-based Tokamak Energy is developing a spherical tokamak fusion machine and holds a large number of related patents. Investors include the UK government and Furukawa Electric, with total funding exceeding USD 250 million. The company is collaborating with the US Department of Energy (DOE) and the UK Department for Energy Security and Net Zero (DESNZ) to upgrade its ST40 spherical tokamak, the first privately-built device to achieve a plasma temperature of 100 million degrees Celsius. Tokamak Energy aims to achieve 500 MW power generation in the US by the 2030s.

US-based Pacific Fusion is pursuing economic viability for a compact fusion machine with pulsed magnetic fusion—an inertial confinement fusion variant—based on a fusion machine concept developed at the Lawrence Livermore National Laboratory. In a Series A funding round led by US venture capital firm General Catalyst, the company raised USD 900 million. Its goal is to realize a commercial fusion machine in the 2030s.

[Article] On Commonwealth Fusion Systems' (CFS) Efforts to Reduce Project Friction

CFS devoted significant time to the site selection process for its compact demonstration plant, SPARC, conducting a review and assessment across 48 states covering all key items among a comprehensive set of criteria.

The company first needed to identify a location where the magnet manufacturing facility, corporate headquarters, and tokamak construction site could be co-located. In order to avoid the cost and complexity of installing expensive new power transmission lines, it was also important to choose a location with existing infrastructure for grid interconnectivity. Accessibility for the collaborating MIT team was also taken into account. Furthermore, identifying a company or a region with a strong and skilled workforce was a matter of high importance.

Another key factor in site selection was the presence of a welcoming community. CFS held direct meetings with all local environmental groups, providing repeated, detailed explanations of the differences in safety between fusion devices and nuclear fission reactors, as well as the company's potential to deliver new clean energy. As a result of these ongoing dialogues, no major issues were raised during public hearings or the public comment process, and CFS was able to secure the understanding and cooperation of the local community.

The company is convinced that active community engagement is essential to from the earliest stages of the project to clearly communicate its position and objectives, minimizing friction during execution.

6.5 International Cooperation in Fusion Energy Development

Several international collaborative initiatives for fusion energy are currently underway in addition to the ITER Project. The following are organized under the frameworks of the International Atomic Energy Agency (IAEA) and the International Energy Agency (IEA):

- International Fusion Research Council (IFRC)
  The IFRC was established by the IAEA in 1971 as an advisory body to the Director General on the Agency's fusion program. It holds annual meetings and promotes research cooperation in the field of fusion energy development, organizes international conferences and technical meetings, provides technical assistance, and more.
- Fusion Energy Conference (FEC)
  The FEC is the largest academic conference in the field of fusion energy research, organized by the IAEA since 1961. It is held biennially, with the 30th conference scheduled to take place in China in October 2025.
- Fusion Power Coordinating Committee (FPCC)
  The FPCC was established by the IEA Governing Board in 1975. It holds annual meetings to coordinate IEA activities in the field of fusion energy development, and provides advice on fusion policy and technical issues to the IEA Committee on Energy Research and Technology (CERT) and other IEA bodies.

Japan also engages in activities such as information exchanges, researcher exchanges, and joint research with partner countries for fusion energy development, based on implementing arrangements concerning fusion cooperation.[63]

- Japan-US Cooperation
  Based on the 2013 Implementing Arrangement on Cooperation in the Field of Energy, the Japan-US Coordinating Committee for Fusion Energy (CCFE) holds annual cooperation meetings. Key participants include the US Department of Energy (DOE), a Fellow from General Atomics, and the Director for International Cooperation on Fusion and Nuclear Energy at the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. These meetings deliberate on collaborative efforts in fusion energy R&D, review reports on joint research conducted in the previous fiscal year, as well as propose and approve joint research projects for the current fiscal year.

- Japan-China Cooperation
  Based on the 2007 Implementing Arrangement on Cooperation in the Field of Magnetic Fusion Energy Research and Development and Related Fields, the Japan-China Joint Working Group (JWG) meets annually. Key participants include the Deputy Director-General, Department of International Cooperation, Ministry of Science and Technology

of China (MOST); the Director of the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP); the Director of the Southwestern Institute of Physics (SWIP); and the Director for International Cooperation on Fusion and Nuclear Energy at MEXT. The meetings deliberate on collaborative efforts in fusion energy R&D, review reports on joint research conducted in the previous fiscal year, as well as propose and approve joint research projects for the current fiscal year.

- Japan-Korea Cooperation
  Based on the 2004 Implementing Arrangement on Cooperation in the Field of Fusion Energy, the Japan-Korea Joint Coordinators Meeting (JCM) in Fusion Energy Research is held annually. Key participants include the Director of the Nuclear and Fusion Energy Cooperation Division, Ministry of Science and ICT (MSIT) of Korea; the President of the Korea Institute of Fusion Energy (KFE); and the Director for International Cooperation on Fusion and Nuclear Energy at MEXT. The meetings deliberate on collaborative efforts in fusion energy R&D, review reports on joint research conducted in the previous fiscal year, as well as propose and approve joint research projects for the current fiscal year.

- Japan-EU Cooperation
  Based on the 1989 Agreement between the Government of Japan and the European Atomic Energy Community for Cooperation in the Field of Controlled Fusion, the Japan-EU Coordinating Committee (CC) for Fusion Cooperation meets annually. Key participants include the Director for Energy Research, Directorate-General for Research and Innovation, European Commission (EC DG-RTD); the Head of the ITER Physics Department, Programme Management Unit, EURO fusion; and the Director for International Cooperation on Fusion and Nuclear Energy at MEXT. The meetings deliberate on collaborative efforts in fusion energy R&D and review cooperation activities for the current fiscal year.
  In addition, Broader Approach (BA) activities under the ITER Project are undertaken as part of Japan-EU cooperation. The BA activities, based on the BA Agreement, aim to complement and support the ITER Project while conducting advanced R&D to establish the technological foundation necessary for the demonstration reactor (DEMO). Specific activities include the construction of advanced fusion devices, the development of durable materials, and preparatory work for the DEMO prototype reactor.
  The DEMO Design and R&D Coordination Centre, the ITER Remote Experimentation Centre, and the Fusion Computational Simulation Centre operate from the International Fusion Energy Research Centre (IFERC) in Rokkasho, Aomori Prefecture, along with the engineering validation and engineering design activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA).
  In addition, JT-60SA is being constructed in Naka City, Ibaraki Prefecture under the Satellite Tokamak Program. JT-60SA is capable of continuously sustaining plasma for

up to 100 seconds, and through experimentation will collect data on plasma stabilization methods and fusion energy handling, thereby contributing to the efficient operation of ITER and the reduction of associated risks.

7. Efforts Toward Industrialization

7.1 Development Trends at National Research Institutes

7.1.1 JT-60SA (Japan Torus-60 Super Advanced) Project[64]

JT-60SA is an international fusion experiment project jointly undertaken by Japan and Europe, located at the Naka Fusion Institute of the National Institutes for Quantum Science and Technology (QST) in Naka City, Ibaraki Prefecture (Table 7-1).

This device is an advanced tokamak fusion machine equipped with superconducting coils, designed as an upgraded version of its predecessor, JT-60U (Table 7-2). JT-60SA's superconducting magnet system is comprised of 18 D-shaped niobium-titanium toroidal field coils, a niobium-tin central solenoid, and 12 equilibrium field coils.

As one of the world's largest superconducting tokamak devices, JT-60SA aims to develop the technologies and conduct plasma physics research necessary before the start of operations at the International Thermonuclear Experimental Reactor (ITER). The project makes use of Japan's prior research achievements and makes further advancements through cooperation with Europe, and plays a vital bridging role between ITER and future demonstration fusion power plants (DEMO) by running in parallel with the ITER program.

The main objectives of JT-60SA project are as follows [64]:

1. Support research to achieve ITER's technical objectives:
   Conduct high-performance operations with plasma shapes similar to ITER and feedback the results to ITER.
2. Complementary (to ITER) research towards a prototype reactor:
   Establish operational methods to maintain high-pressure plasma for long durations (approximately 100 seconds) with the aim of realizing high-output fusion machines.
3. Human resource development:
   Train researchers and engineers capable of leading fusion energy R&D like the ITER program.

Table 7-1 JT-60SA device specifications[65,66]

Fusion thermal output (Maximum DD fusion thermal output)	3.6 MJ (270 kW)
Q value (Fusion thermal output/external heating input)	< 1
Combustion time driven by induced current	Approximately 100 seconds
Major radius (R)	2.97 m
Small radius (a)	1.18 m
Plasma current (Ip)	5.5 MA
Elongation ratio (κ_{95}) at the 95% magnetic flux surface/separatrix	1.93
Angle (δ_{95}) at the 95% magnetic flux surface/separatrix	0.5
Safety factor (q_{95}) at the 95% magnetic flux surface	3.0
Toroidal magnetic field (BT) at radius 2.97 m	2.25 T
Plasma volume	133 m^3
Input power via external heating and electrical current drive device	23.5 MW

Table 7-2 Construction and operational history of JT-60SA

Chronological Table	Overview
January 2013	Assembly started
March 2020	Assembly completed
October 2023	First plasma achieved

7.1.2 LHD Project[67]

The Large Helical Device (LHD), operated by the National Institute for Fusion Science (NIFS), is one of the world's largest stellarator devices and employs a magnetic configuration known as the "heliotron" configuration. This configuration, the first in the world to employ superconducting coils for all coils in a magnetic confinement device, enables the formation of a helical magnetic field with a single set of external coils, thereby achieving excellent steady-state operation capability while stably confining plasma.

Table 7-3 LHD device specifications

Plasma major radius	33.9 m
Plasma minor radius	0.6 m
Plasma volume	Approximately 30 m³
Magnetic field intensity	3 T
Device outline	13.5 m
Device weight	1,500 t
Input power via external heating and electrical current drive device	36 MW

Since achieving its first plasma in March 1998, experimental research has been conducted at the LHD for a quarter of a century, producing numerous significant achievements. In particular, the LHD achieved a plasma ion temperature of 120 million degrees Celsius during the deuterium experiments launched in March 2017, contributing to research on high-performance plasmas essential for realizing practical fusion energy. The device has also demonstrated steady-state operation capabilities, including sustaining high-temperature plasma for more than 3,000 seconds.

The deuterium experiment program concluded in December 2022, and in FY2023, the Academic Research Platform LHD Project was launched, marking a transition to a new research phase that builds on past achievements. Under this international collaboration, high-resolution diagnostic instruments are used to observe the internal structure of ultra-high-temperature plasmas, with the goal of elucidating complex phenomena common not only to fusion reactions but also to cosmic and astrophysical plasmas.

During the deuterium experiments, safety concerns were raised over the potential generation of tritium. In response, NIFS reached an agreement with the local municipalities of Toki City, Tajimi City, and Mizunami City in Gifu Prefecture, implementing the following safety measures:

- Compliance with all relevant laws and regulations
- Limiting radiation dose at the site boundary to 50 μSv/year or less

- Prohibition of fusion experiments using tritium
- Continuous monitoring and measurement of environmental radiation and pollution prevention measures
- Prior explanation of research plans and activities, along with public briefings for local residents

Furthermore, Gifu Prefecture and the three municipalities jointly established a Safety Monitoring Committee to oversee the institute's activities, review measurement results, and monitor environmental neutron dose and tritium concentration in the surrounding waters. In addition to establishing safety assessment and monitoring systems, NIFS implemented outreach and engagement activities with stakeholders to ensure the effectiveness of these safety measures.

7.2 Trends in Private-Sector Developments [25]

7.2.1 Kyoto Fusioneering/Starlight Engine: Fusion by Advanced Superconducting Tokamak (FAST) Project

Kyoto Fusioneering Ltd., a Kyoto University spin-off founded in October 2019, is a start-up company specializing in the engineering of fusion energy plants and the development of advanced technologies. Its core business areas include the research, development, design, manufacturing, and integration of essential systems and components for fusion plants, such as plasma heating (gyrotron) systems, fuel cycle systems, and thermal cycle systems.

In November 2024, Kyoto Fusioneering launched the FAST Project, a private-sector-led industry-academia collaborative initiative pursued in partnership with domestic and international researchers and industrial partners. The project aims to develop a tokamak fusion device that will generate fusion power in the 2030s (Table 7-4). To accelerate the initiative, Starlight Engine Inc. was established in April 2025 to oversee the entire FAST Project. The company will lead the development of FAST's technologies, business strategies, fund-raising, site selection, and supply chain construction.

Table 7-4 FAST device specifications

Fusion output	50-100 MW
Neutron wall load	300-1,000 kW/m²
Discharge time	Approximately 1,000 seconds
Estimated full power operating time	Approximately 1,000 hours

The FAST device is designed as a low-aspect-ratio tokamak equipped with high-temperature superconducting (HTS) coils, enabling demonstration tests necessary for small, economically viable fusion plants. It aims to address the following technical challenges:

1. Demonstration of D-T burning: Generation, sustainment, and control of burning plasma using deuterium (D) and tritium (T) in deuterium-tritium (D-T) fusion reactions.
2. Energy extraction and utilization: Extraction of the energy produced by fusion reactions, its conversion (e.g., into electricity), and practical utilization.
3. Tritium generation and fuel cycle demonstration: Demonstration of technologies for breeding, extracting, and utilizing tritium, the fuel for fusion reactions.
4. System integration: Development and demonstration of plant technologies for integrating a fusion energy system and operating it safely and sustainably.

The project's organizational structure consists of a researcher-led team responsible for design, planning, and operation, working in collaboration with domestic and international researchers, primarily specialists in plasma physics and fusion machine engineering. It also involves close cooperation with industrial partners, mainly member companies of the J-Fusion consortium—including Mitsui & Co, Mitsui Fudosan, Mitsubishi Corporation, Marubeni Corporation, Fujikura, Kajima Corporation, and Furukawa Electric—to advance plant design, safety analysis, site solicitation, and site preparation. In addition, the project will collaborate with international partners in the US, the UK, Canada, and other countries.

The FAST Project aims to generate power* in the 2030s, conducting engineering tests necessary for the industrialization of fusion energy and bridging existing technical gaps (Figure 7-1).

*In this context, "generate power" refers to the establishment of technologies for heating a blanket with fusion reactions, extracting the heat, driving a turbine via a heat exchanger, and sustained generation of electricity. The goal is to generate 2,500 kWh (10 MW of electricity, equivalent to 20,000 households, for 15 minutes).

Figure 7-1 FAST (Fusion by Advanced Superconducting Tokamak) Program

7.2.2 Helical Fusion: Helix Program

Helical Fusion Co., Ltd., founded in October 2021, is a fusion development company dedicated to the early realization of fusion energy. Spun out from the National Institute for Fusion Science (NIFS), the company builds on decades of research with the Large Helical Device (LHD)—one of the world's largest stellarators—and the long-term FFHR fusion power plant program, carrying forward this expertise to develop a next-generation stellarator machine.

Helical Fusion is addressing two of the most critical challenges in fusion machine engineering: high-temperature superconducting (HTS) coil development and liquid-metal blanket development.

The company is constructing a compact intermediate device, called Helix HARUKA, to integrate these technologies and demonstrate their performance in long-duration operation. Looking ahead, it aims to realize a 50–100 MW-class pilot power plant, called Helix KANATA, by the mid-2030s (see Figure 7-2).

This first plant will go beyond proof of gross power output. It is designed to demonstrate net electricity generation of 50–100 MW under steady-state conditions—delivering more power than is consumed—thereby moving beyond scientific demonstration and establishing a credible pathway to commercial fusion power. The conceptual design has been published in peer-reviewed journals,[68] providing assurance of its scientific and engineering soundness.

The company's core strengths are its technical expertise and development capability. Working in collaboration with leading equipment manufacturers, Helical Fusion is advancing innovative, proprietary technologies such as flexible HTS cables capable of forming complex geometries, and liquid-metal blankets with integrated divertor functionality. Distinct from projects focused solely on research or experimental validation, Helical Fusion takes an integrated, commercialization-oriented approach—optimizing systems not only for physics performance but also for economics, maintainability, and safety.

A further hallmark of its strategy is its commitment to open innovation, pursuing joint development with Japan's advanced manufacturing companies to accelerate progress toward a viable fusion industry.

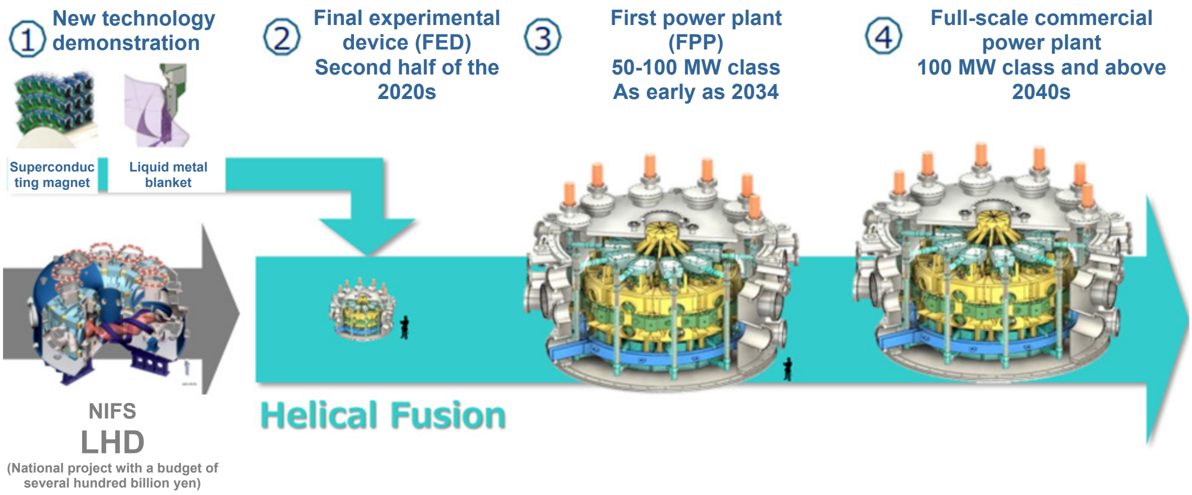


Figure 7-2 LHD and Helical Fusion's approach towards commercialization

7.2.3 EX-Fusion: Laser Fusion Machine

EX-Fusion Inc. is the first private company in Japan aiming to realize commercial power generation through laser fusion. The company is engaged in the development of innovative technologies that use high-power lasers to instantaneously compress and heat deuterium and tritium, thereby initiating a clean and sustainable fusion reaction.

EX-Fusion operates its own research facility in Hamamatsu City, Shizuoka Prefecture, where it is developing essential component technologies for the realization of commercial fusion machines. Specifically, the company is focusing on the development and integrated demonstration of core laser fusion technologies, including continuous target delivery, high-precision target tracking, and precision control and irradiation of high-power pulsed lasers for repetitive operation.

Building on this research and development foundation, EX-Fusion plans to demonstrate continuous neutron generation by 2027, and to achieve steady-state energy generation through laser fusion by 2030. Leveraging these achievements, the company aims to commence operation of a commercial fusion machine around 2040, steadily advancing its technology development (Figure 7-3).

In addition, EX-Fusion has recently opened a laser processing facility in Kyoto, promoting the early social implementation of laser fusion technologies by applying its cutting-edge expertise cultivated in the research to a wide range of industrial sectors. The company is committed to driving an energy revolution through laser fusion technology and contributing to the creation of a sustainable global society.

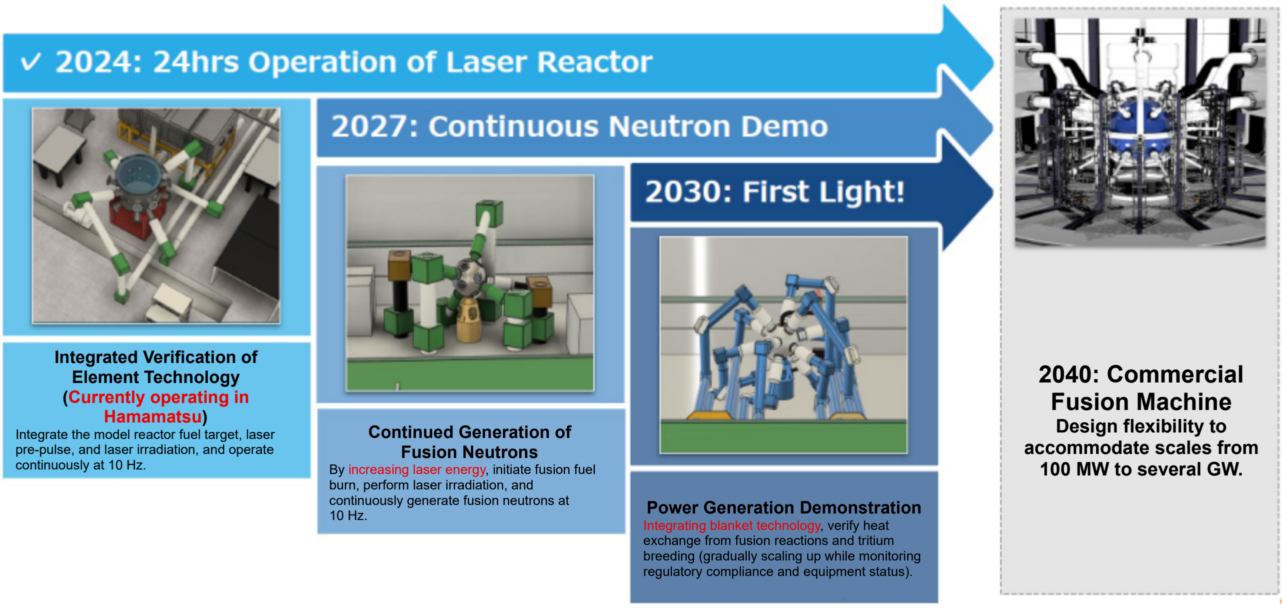


Figure 7-3 EX-Fusion development roadmap

7.2.4 LINEA Innovation: FRC-Mirror Hybrid Fusion Machine

LINEA Innovation Inc. is a start-up founded on research achievements from Nihon University and the University of Tsukuba, aiming to develop a commercial fusion machine based on Proton (light hydrogen)-boron-11 fusion (p-^{11}B reaction)(Figure 7-4). Unlike deuterium-tritium (D-T) reactions, p-^{11}B fusion produces no neutrons and generates no radioactive waste, making it a highly safe energy source of growing interest.

Realizing p-^{11}B fusion has long been considered extremely challenging, as in conventional thermal fusion approaches pursued by most fusion research institutes and companies, p-^{11}B reactions require plasma temperatures even higher than those for D-T reactions. To overcome this challenge, LINEA Innovation is pursuing a non-thermal approach, distinct from conventional methods. It adopts a hybrid configuration that combines the features of the field-reversed configuration (FRC) and mirror magnetic fields, aiming to induce non-thermal p-^{11}B reactions.

The company is looking to demonstrate electricity generation via p-^{11}B reactions in the early 2030s and commercial power generation by the mid-2040s. To this end, in February 2024, LINEA Innovation signed a joint research agreement with the Plasma Research Center of the University of Tsukuba to begin studies on FRC-mirror hybrid configurations. In August of the same year, it concluded a joint research agreement with the Plasma Physics Lab, Department of Physics, College of Science and Technology, Nihon University, to advance research toward the hybridization of FRC and mirror approaches.

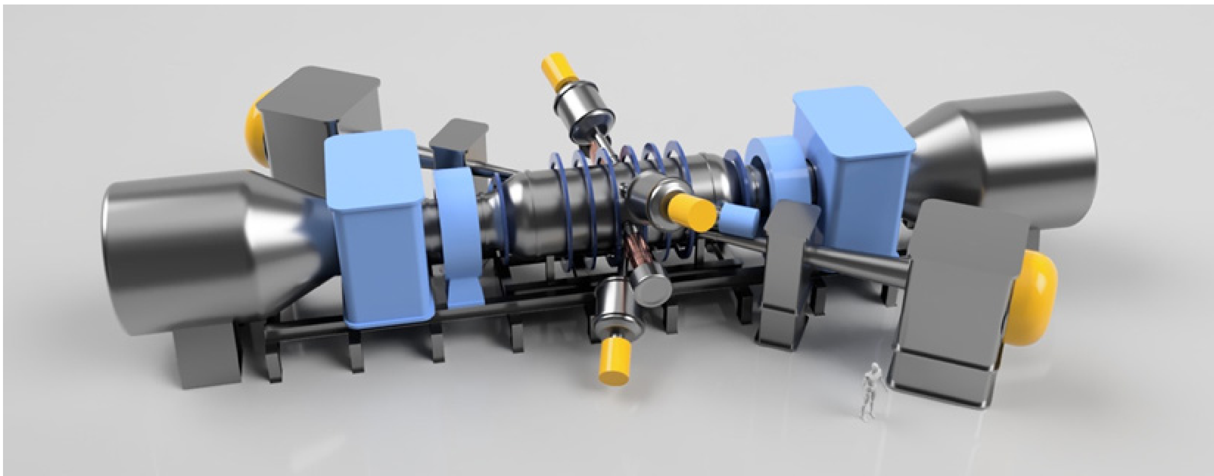


Figure 7-4 Concept of FRC-mirror hybrid fusion machine

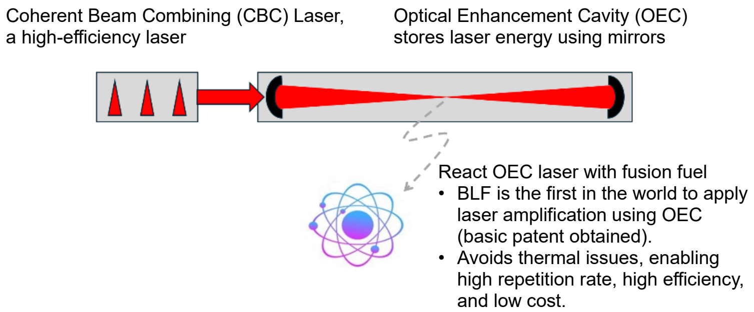
7.2.5 Blue Laser Fusion LLC: Laser Fusion

Blue Laser Fusion LLC (BLF) aims to realize laser fusion at an early stage using its proprietary optical enhancement cavity (OEC) method. In April 2025, BLF established the Osaka University—Blue Laser Fusion Energy Collaboration Research Center together with Osaka University, combining the university's broad academic resources with state-of-the-art optical science and technology to accelerate research and development.

In 2025, Lawrence Livermore National Laboratory (LLNL) in the US achieved a historic milestone using 192 glass lasers (10 kJ-class) with a total input energy of approximately 2 MJ, producing an output of 8 MJ (a gain of 4). While this was a major breakthrough demonstrating the feasibility of laser-driven fusion energy, the thermal load accumulated in the glass laser medium limits operation to only a few shots per day, leaving scalability toward commercialization as a challenge.

In this regard, BLF's OEC approach offers a decisive advantage: it avoids placing thermal load on the laser medium (glass, crystals, etc.) by applying high-reflectivity mirror and optical storage technologies proven in gravitational wave observatories such as LIGO and KAGRA, potentially enabling continuous irradiation at 1 Hz or higher. This would fundamentally overcome the cooling and repetition-rate constraints of conventional glass lasers, making the OEC laser a promising driver for practical laser fusion, where high efficiency and high repetition rates are essential.

BLF plans to advance OEC laser development and ignition experiments on fusion materials using Osaka University's laser facilities in phases under this collaborative research framework, aiming to complete a demonstration-reactor-scale laser system around 2030 (Figure 7-5).



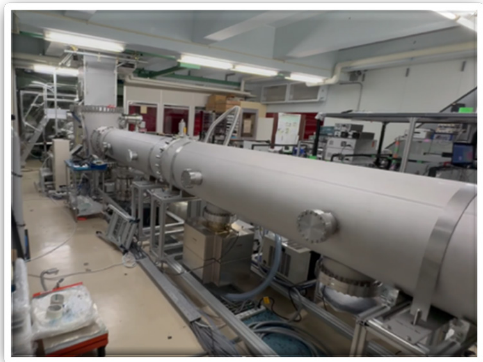


Figure 7-5 Principle of an OEC laser (left), 15 m OEC device installed at Osaka University (right)

8. Towards the Industrialization of Fusion Energy

Fusion energy is expected to serve as a stable, decarbonizing energy source. It emits no CO_2 during operation, its fuel can be procured in virtually unlimited quantities, and it possesses inherent safety characteristics–such as the automatic cessation of the reaction unless deliberately maintained.

With private-sector-led development accelerating worldwide and international competition already underway, Japan has also set forth a vision for the industrialization of fusion energy in the Fusion Energy Innovation Strategy (2023), not as a distant prospect, but as a strategy looking ahead to the next decade.

Among its components, the "Basic Approach to Ensuring Safety" has been formulated as one of the "Strategies for the Development of the Fusion Industry." The industrial sector supports this policy of advancing technology development and social implementation by private companies on the premise of ensuring safety. In particular, beyond statements from business operators, government communication of the "Basic Approach to Ensuring Safety" is vital to achieving socially acceptable fusion energy.

Furthermore, rational legislative measures taken by the government will serve as an important indicator for enhancing the business environment outlook for many players in the industrial sector seeking to enter this industry, thereby facilitating sufficient investment in the sector.

Bearing in mind the timeline leading up to technological demonstrations (including power generation) in the 2030s, and to ensure the smooth dissemination of commercial fusion machines thereafter, it is important to strengthen collaboration among industry, government, and academia in the field of safety. To this end, J-Fusion will focus its efforts on the following points:

- ✓ Promotion and presentation of policy directions for legal frameworks and the decision-making process/timeline
- ✓ Promotion of the creation of opportunities for innovation
- ✓ Communication and public awareness regarding safety
- ✓ Promotion of sites and locations secured through collaboration between operators and the government
- ✓ Continued assurance of opportunities for dialogue among industry, government, and academia during regulatory development and application phases

To achieve and accelerate the above points, it is imperative to establish a rational and flexible regulatory framework. At present, fusion devices are not subject to the Reactor Regulation Act. It is therefore necessary to specifically consider a policy whereby safety reviews concerning the disposal of radioactive waste, fuel management, and other matters are conducted on the basis of the Act on the Regulation of Radioisotopes and Related Matters (RI Act). In doing so, progress can be made through regulatory reviews tailored to different methods and the characteristics of the various materials used, rather than relying solely on statutory amendments. This ensures technological diversity through flexible and prompt response. This is essentially particularly in relation to risks such as material damage caused by high-energy neutron generation, radiation management, and hazards associated with high-power lasers and high-pressure systems, as risk-based regulations should be made through a graded approach. In addition, with early commercialization of fusion energy plants in mind, the design of compensation systems for accident risks or waste management should also be regarded as an important consideration.

Looking ahead, it is necessary to expedite legislative development in view of the operational demonstrations coming in the 2030s. To that end, J-Fusion will advance initiatives to deepen dialogue among project proponents, regulatory authorities, industry, and the general public.

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