The Nuclear Fusion Distillate

An Energy Technology Distillate from the Andlinger Center for Energy and the Environment at Princeton University

This Distillate was researched, synthesized, and written by 10 Ph.D. students in the Princeton Energy and Climate Scholars (PECS) program at Princeton University, along with faculty mentor, Robert Socolow.

The fusion distillate is written for the reader who has an appetite for technological argument but has no background and no comfort even with algebra. It treats both technology and policy and seeks be evenhanded.

Professor Socolow would welcome your comments and feedback regarding this distillate. Please send your response to Robert H. Socolow socolow@princeton.edu.

Fusion Energy

via Magnetic Confinement

An Energy Technology Distillate
from the Andlinger Center for Energy and the Environment at Princeton University

Contributors

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Prologue

The goal of this report is to inform the reader about the challenges facing magnetic confinement nuclear fusion technology, which could someday provide the planet with a new and unique source of energy. Like the other Andlinger Center Energy Technology "Distillates," this Distillate aims to provide succinct yet substantive information to policymakers, educators, students, and other citizens – to fill a gap between presentations in textbooks and in the popular literature.

This Distillate was researched, synthesized, and written by 10 Ph.D. students in the Princeton Energy and Climate Scholars (PECS) program at Princeton University, along with our faculty mentor, Robert Socolow. PECS is a platform that enables a group of Ph.D. students working on disparate aspects of energy and climate to have an interdisciplinary exchange of ideas. The students involved in this Distillate have a range of expertise: biogeochemistry, climate modeling, ecology, electrical engineering, psychology, and public policy. Notably, none of us is engaged in a dissertation related to nuclear fusion.

The lack of fusion scientists among the authors has required significant effort on our part to learn and understand the intricacies of the fusion field. We were aided by extensive consultations with experts. We hope that the reader will benefit from our collective learning process and our fresh perspective on the fusion enterprise. An exposition emphasizing objectivity may be particularly helpful for fusion because the field is currently conducting expensive experiments that compete for very limited government funding in many nations, resulting in discourse that may at times be hindered by the high stakes between competing approaches and projects.

A special challenge to our objectivity arises from the fact that the Princeton Plasma Physics Laboratory (PPPL) is located at the University. Although we consulted with several fusion experts at PPPL, this report was written independently of PPPL and does not represent its views. Nonetheless, the reader may well anticipate that any document from Princeton will present fusion's potential to become a future energy generation option in an excessively favorable light. We have sought to write an impartial and rigorous assessment, the kind that we would most want to read ourselves. In the process, we hope we have written a document that will be useful for every reader with an appetite for introductory technological analysis and a desire to understand nuclear fusion as an energy source.

Article 1: Overview

In the current century the world faces a dual challenge: providing the energy that enables continued growth in desired human activity, while limiting the severity of climate change by constraining the emissions of carbon dioxide from fossil fuels. Although this dual challenge is expected to be met in part by efficient use of energy and extensive deployment of already well-envisioned low-carbon energy sources, additional low-carbon options could help secure a robust path to sustainable global development. Nuclear fusion energy may be such an option, provided that significant progress in several areas of science and technology is made in the next few decades.

Fusion-generated energy would be uniquely valuable because of a combination of characteristics not shared by any existing technology:

1) Fusion could dependably provide energy at a sufficient scale to meet a significant fraction of global demand.
2) Locations for fusion plants include sites where renewable energy sources are unsuitable.
3) Fusion power is expected to have low impact on public health and local environments.
4) Fusion power has no direct carbon dioxide emissions. The indirect emissions that are associated with plant construction and fuel production are modest.
5) The global supply of fusion fuels is essentially inexhaustible. Lithium and deuterium extracted from seawater could provide enough fusion fuel to meet foreseeable energy demand for millions of years.

Several significant challenges help explain why the multiple benefits of fusion energy have not yet led to its presence in the global energy system, even though the theory of fusion reactions was developed in the 1920s and 1930s. The most direct challenges are in science and technology. Nuclear fusion is the method by which the Sun creates its energy, and replicating such a process on Earth requires recreating conditions comparable with those found in the Sun's core. The temperature of the fusion fuel must be raised to approximately 200 million degrees Celsius, *versus* 15 million degrees Celsius in the core of the Sun. At such temperatures, the fuel is fully ionized, that is, the fuel's atoms have been stripped of all their electrons. This distinctive state of matter is called "plasma." Magnetic confinement uses magnetic fields to retain plasma heat and to control plasma movement while energy is produced within the plasma by nuclear reactions.

Creating, maintaining, and manipulating a high-temperature plasma are unique scientific challenges. Basic questions in the science of plasma physics and applied questions related to engineering and materials have been addressed in both small and large facilities, but many questions can be tested only in the largest facilities, which have become steadily more expensive.

Early research focused on plasma control and limited the number of nuclear fusion events in order to reduce complications. Now the frontier includes "burning plasmas," where enough fusion reactions occur to maintain the high temperature of the plasma with little or no external heating. The behavior of a burning plasma is new territory for science.

The scientific, technological, and economic challenges of fusion energy research go hand in hand with the policy challenges of fusion energy. Because fusion research requires large and long-term financing, funding has come primarily from governments rather than private investors. However, in national politics, it is difficult to sustain many decades of investments on the scale of hundreds of millions of dollars annually when the outcomes are uncertain and the end goal – a commercial reactor – will at best be economically competitive decades in the future. The fusion endeavor struggles to fund expensive research facilities and long-term horizons with bounded and fluctuating budgets.

One way that the fusion community is dealing with financial challenges is by forming international collaborations to pool funds for its larger experiments. The most ambitious collaboration in fusion is the International Thermonuclear Experimental Reactor (ITER), which is currently under construction in France. It will be discussed at some length in this Distillate. ITER is expected to allow for extensive experimentation under burning plasma conditions.

Magnetic confinement fusion is one of the two principal approaches to achieving nuclear fusion energy currently being explored. The other is inertial confinement fusion, which uses pulses from multiple lasers or particle beams to squeeze tiny pellets of fuel and trigger a rapid succession of fusion reactions. Both magnetic and inertial confinement fusion are based on the same nuclear fusion reactions, but due to their vastly different configurations, the obstacles in these two paths to commercial fusion energy are entirely different. Here, we focus nearly exclusively on magnetic confinement fusion, presenting the major technological and economic issues associated with its potential for commercial success. To further bound our Distillate, we do not discuss the relatively few, small-scale, private-sector-funded fusion ventures that are seeking alternatives to the mainstream government-funded approaches.

A commercially competitive fusion power plant would be a remarkable human achievement. As the science unfolds, however, it is possible that the emergent technological, economic, and political requirements will not reveal a path forward. For now, achieving competitive nuclear fusion energy is an open-ended endeavor.

The remainder of this Distillate consists of five articles. Article 2, "Key Concepts and Vocabulary," provides background for the later articles. Article 3, "Technology," presents some of the basic science relevant to fusion energy and a few of the central technical challenges being addressed in current fusion research. Article 4, "Economics" discusses issues likely to determine the prospects for commercial fusion: the costs of reactor construction and ongoing maintenance, the strength of climate policy, and the success of fusion's competitors. Article 5, "Fusion and Fission," discusses how well nuclear fusion power will address several of the vexing problems that currently challenge nuclear fission power. Article 6, "Politics and Progress," reviews the current global effort to develop nuclear fusion.

Article 2: Key Concepts and Vocabulary

Power and energy

Energy is a fundamental physical quantity that comes in many different forms, and the quantity of energy does not change as it is transformed from one form to another. In a magnetic fusion reactor, there are many forms of energy. Electric currents flowing through coils of conducting wires create magnetic energy in the form of magnetic fields that confine the region where fusion occurs. During a fusion event, injected fuel reacts and releases nuclear energy that is then transformed into kinetic energy of the fusion products. These fusion products slow down through collisions with the surrounding material, transforming their kinetic energy into thermal energy. Some of the thermal energy sustains the plasma temperature, and some is converted into electricity. Finally, some of the electricity is used within the power plant to power magnets and other auxiliary systems, but most of the electricity is sent on transmission lines to provide consumers with power for refrigerators, lights, computers, and many other devices.

Although amounts of energy are expressed in many different units, depending on the country and the context, the scientific community uses a unified system of joules for macroscopic energy and electron volts for energy at the scale of atoms and nuclei. Associated with the joule is a rate of energy consumption, one joule per second, which is called the watt. Two multiples of the watt are widely used: the kilowatt (1,000 watts) and the megawatt (one million watts). Most nuclear fission power plants today have the capacity to produce electricity at a rate of about 1,000 megawatts, and fusion plants are currently expected to have a similar capacity.

At the microscopic level, the reference unit energy, the electron volt (eV), is approximately six quintillion (six billion billion, or six followed by 18 zeros) times smaller than the joule. One million electron volts, a common unit for nuclear science, is abbreviated MeV.

Atoms, nuclei, electrons, ions, plasma

Matter is made of nuclei and electrons. When matter is not very hot, it is structured as atoms, each of which has a tiny, positively charged, dense nucleus at its center. The nucleus is made of protons (p, positively charged) and neutrons (n, electrically neutral). Surrounding the nucleus are electrons, each carrying one negative electric charge. In an electrically neutral atom, the positive charge of the nucleus is balanced by the negative charges of electrons. When there is not perfect balance, the atom is called an ion; an ion can be positively or negatively charged.

At a very high temperature, such as that created in a fusion reactor, nearly all the electrons become free from their nuclei, and the result is a state of matter, called “plasma,” where 1) nearly all matter is ions and electrons, and 2) overall, there is no (or very little) net electric charge. A plasma behaves fundamentally differently from a gas because in a plasma the particles attract or repel one another over a distance through electromagnetic forces, but in a gas the particles interact by colliding with each other. Plasmas are called the fourth state of matter, alongside solids, liquids, and gases. The field of plasma physics examines the behavior of plasmas, including the conditions under which they are stable or unstable. Our Sun is a plasma whose core is at a temperature of 15.6 million degrees Celsius. The temperatures in fusion research reactors are even higher.

Isotopes and radioactivity

The chemical behavior of an atom is determined by its electrons. For example, a neutral atom with 26 electrons (iron) will have a nucleus with 26 protons. The chemical behavior of an atom does not depend on how many neutrons are in the nucleus, and the nuclei of an element can have varying numbers of neutrons. Atoms with the same number of protons but different numbers of neutrons in their nuclei are called isotopes of one another. A widely used notation for isotopes provides the name of the atom and the total number of protons and neutrons. Iron-56, one of the isotopes of iron, has a total of 56 neutrons and protons; since the iron atom has 26 electrons balancing a total positive nuclear charge of 26, it has 26 protons and 30 neutrons. Iron-56 is also written as ^{56}Fe; Fe is the chemist’s abbreviation for iron.

Isotopes can be either stable or radioactive. All stable isotopes are found on Earth, along with some radioactive isotopes. The stable isotopes in the Earth’s crust occur in specific proportions. For example, ^{56}Fe happens to be the most common isotope of iron in the Earth’s crust, accounting for 92 percent of the iron in the crust; the next most common is ^{54}Fe, accounting for six percent. As for radioactive isotopes of iron, these can be created in nuclear reactions. For example, when the steel in a nuclear fission or fusion reactor is exposed to bombardment by energetic neutrons, some of the resulting isotopes are the iron isotopes, ^{55}Fe, ^{59}Fe, and ^{60}Fe.

Every radioactive isotope has a half-life, meaning that if a given amount of an isotope is present at a given moment, then – as a result of radioactive decay – half as much will be present after one half-life. The other half will have been transformed into another isotope, usually an isotope of another element. The half-life of ^{59}Fe, for example, is 45 days; after 45 days, half of it has become ^{59}Co, a stable (non-radioactive) isotope of cobalt, and half is still ^{59}Fe. After 90 days (two half-lives) three quarters has become ^{59}Co. The half-lives of ^{55}Fe, ^{59}Fe, and ^{60}Fe are 2.7 years, 45 days, and 2.6 million years, respectively. They are the radioactive isotopes of iron with the three longest half-lives.

Importantly for fusion, there are three isotopes of the hydrogen nucleus: the ordinary hydrogen nucleus (called the proton, written as either ^{1}H or p, consisting of one proton and no neutron); the deuterium nucleus (called the deuteron, written as either ^{2}H or D, consisting of one proton and one neutron); and the tritium nucleus (called the triton, written as either ^{3}H or T, and consisting of one proton and two neutrons). ^{1}H and ^{2}H are the two stable isotopes of hydrogen, and ordinary hydrogen is far more prevalent on Earth. Only one out of every 6,500 hydrogen atoms at the Earth's surface is deuterium. Tritium is radioactive, with a half-life of 12.3 years. Due to its short half-life almost no tritium exists naturally on Earth.

Nuclear reactions

Just as chemicals react to produce other chemicals in a chemical reaction, nuclei can react to produce other nuclei in a nuclear reaction. Many reactions in both cases also produce energy. For example, when gasoline burns, this is a chemical reaction that produces carbon dioxide and water and releases energy; energy is also released in the nuclear reactions discussed below. Nuclear reactions typically release roughly a million times more energy than chemical reactions.

For a nuclear fusion reaction to be possible, the total number of protons must be the same in the reactants and the products, and the equality must also hold true for the neutrons. We give two examples of energy-producing nuclear reactions important to fusion here:

Reaction 1: $^{2}H + {}^{3}H \rightarrow n + {}^{4}He$ + 17.6 MeV. The reactants are a deuteron and a triton, with a total of two protons and three neutrons. The products are a neutron (n) and a "helium-4" nucleus. The helium-4 nucleus has two protons and two neutrons. (It has a special name, the "alpha" particle.) Thus, in all, the two products have two protons and three neutrons, just as the reactants do. Also, 17.6 million electron volts (MeV) are released, initially in the form of the kinetic energy of the two products. Of all the nuclear reactions, this "deuterium-tritium" or "D-T" reaction is the least difficult to produce in a hot plasma and accordingly is the focus of most of the work seeking to commercialize fusion energy. It will be discussed extensively in this distillate.

Reaction 2: $n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He$ + 4.8 MeV. The lithium atom has three electrons, and this particular lithium nucleus, the lithium-6 nucleus, has three protons and three neutrons. Thus, there are a total of three protons and four neutrons in the reactants. There are also three protons and four neutrons in the products, which are tritium and the helium-4 nucleus. Reaction 2 plays a critical role in D-T fusion by creating tritium from lithium. Lithium is an abundant resource, but tritium, as noted above, is essentially absent from the Earth and yet is needed as a reactant for D-T fusion. Reactions 1 and 2 can be combined so that the neutron produced in Reaction 1 becomes a reactant for Reaction 2. Then the net result is that two ^{4}He nuclei are produced, and a deuterium nucleus and a lithium-6 nucleus are consumed. Tritium is destroyed in the first reaction but replenished in the second. The two reactions produce a total of 22.4 MeV.

Magnetic confinement of charged particles

A magnetic confinement fusion reactor features large and very strong magnets. The magnetic fields created by these magnets can be shaped into specific configurations that force all of the charged particles in the plasma to move within a specific region of the fusion reactor's vacuum vessel. One then says that the plasma is "confined."

At a fusion plant with conventional magnets, the power requirements for the magnets can become a significant fraction of the energy produced by the power plant. However, when currents run along wires that are made of a particular class of materials called "superconductors," no power is required to sustain the current and the magnetic fields. Magnets produced by current flowing in wires made from superconducting materials are called superconducting magnets. The world's largest and strongest superconducting magnets are being designed for use in fusion test facilities.

To date, no material has been found that is superconducting at room temperature, but some materials are superconducting at very low temperatures, only a few degrees above absolute zero

(zero Kelvin degrees, which is equivalent to -273.15 degrees Celsius and -459.67 degrees Fahrenheit). Thus, to enable superconducting magnets to be used, a large amount of cooling equipment must be installed at a fusion plant. However, even taking the cooling equipment into account, superconducting magnets require much less power than ordinary magnets.

In the most common configuration, a plasma is confined in a space resembling a donut, also called a torus. Figure 2.1 differentiates the two kinds of loops on a torus: toroidal and poloidal. In fusion research, one speaks of toroidal and poloidal magnetic fields.

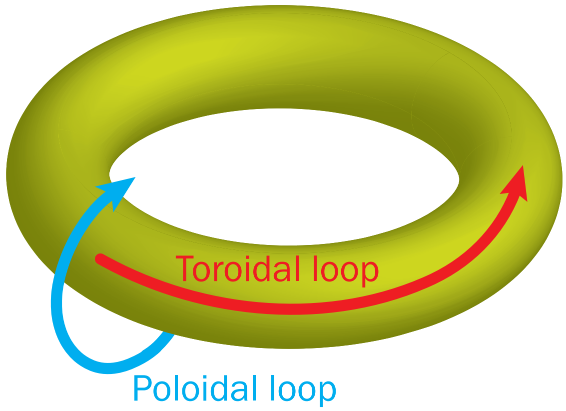

Figure 2.1: The two kinds of circular paths around a donut (torus) are identified.

Article 3: Technology

We consider only magnetic confinement fusion here. The history of magnetic confinement fusion research can be split roughly into two eras: From the 1950s to the 1990s fusion research focused mostly on magnetic confinement and the physical properties of the core of the plasma. The hydrogen in the plasmas was usually deuterium without tritium, because in an all-deuterium plasma the D-D nuclear reactions (reactions between pairs of deuterium nuclei) are rare at the temperatures of the laboratory plasmas and, as a result, little radioactivity builds up in the walls of the reactors. However, the small amount of radioactivity was useful for diagnosis of the detailed performance of the plasma; a plasma made of ordinary hydrogen would produce too little radioactivity to serve this purpose.

We are now in the second era, where the goal is to achieve a "burning plasma" – a plasma heated predominantly by the energy from fusion reactions occurring within the plasma, rather than by external sources. The new era began cautiously in the 1990s when deuterium-tritium (D-T) plasmas, which are much more likely to lead to nuclear reactions than D-D plasmas, were created in some reactors. Also, research attention shifted to the edges of the plasma where heat is lost and materials are damaged. The new era features the intertwining of two strands: the science of plasmas and the science of nuclear fusion reactions.

Here, we first introduce these strands separately. Then we present some of the issues that arise when they are combined, such as the burning plasma, neutron bombardment of structural materials, and the regeneration ("breeding") of tritium.

Occasionally, for specificity, we refer to the expected performance of the International Thermonuclear Experimental Reactor (ITER), the large international magnetic confinement research project slated to begin operating in 2026. We discuss the political history of ITER in Article 6 of this Distillate.

Magnetic Confinement

Tokamaks and stellarators

The principal configurations for plasma confinement being explored today have the shape of a donut, formally called a torus. On the torus there are two different directions, toroidal and poloidal (see Figure 2.1). Toroidal field magnets produce magnetic fields in the toroidal direction, and poloidal field magnets produce magnetic fields in the poloidal direction *[1]*. The combination of toroidal and poloidal magnetic fields confines the plasma, steering it away from solid surfaces.

Fusion research is focusing on two toroidal configurations: the tokamak and the stellarator. Tokamaks were initially developed in the Soviet Union at the same time as stellarators were being developed in the United States and elsewhere. Tokamaks proved able to achieve better confinement and higher temperatures and became the dominant design. ITER is a tokamak. However, stellarators may be making a comeback because they have advantages in two areas relevant to commercial viability: 1) stellarators have intrinsic advantages in sustaining a plasma continuously, and 2) stellarators may be better at avoiding the large-scale disruptive instabilities that can seriously damage plasma-facing components.

Figure 3.1 shows the complex array of magnets that confines a plasma in a generic tokamak. The tokamak, in addition to its toroidal and poloidal magnets, has a central structure running through the donut hole, called a solenoid. When the current in the coils of the solenoid changes, it induces a voltage that drives the plasma's current. (A transformer on an electric utility's distribution network transfers power by the same inductive process.) The ITER tokamak will have a central solenoid 13 meters high that weighs 1,000 tons, as well as 18 D-shaped toroidal-field coils and six ring-shaped poloidal-field coils. Construction of these components in the ITER member countries has begun (see Article 6).

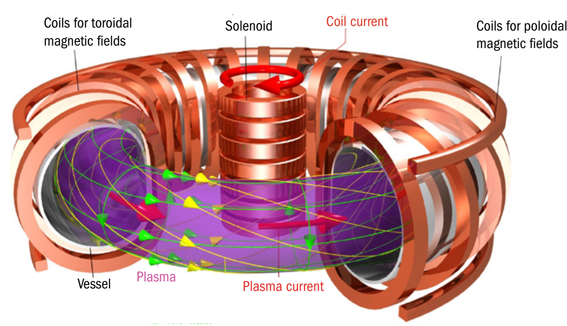

Figure 3.1: Magnetic coils and fields in a tokamak reactor. Note that the coils for the toroidal magnetic fields follow a poloidal path and the coils for the poloidal magnetic fields follow a toroidal path. *Image credit:* Max Planck Institute for Plasma Physics.

Figure 3.2 shows configuration of the most recent stellarator, Germany's Wendelstein 7-X (W7-X); it began running in the summer of 2015. Stellarators do not have a central solenoid, but instead have a complex three-dimensional geometry that is an engineering challenge to manufacture and is currently responsible for added costs. Stellarators are benefiting from the arrival of supercomputers powerful enough to design an optimal magnetic coil configuration for plasma confinement.

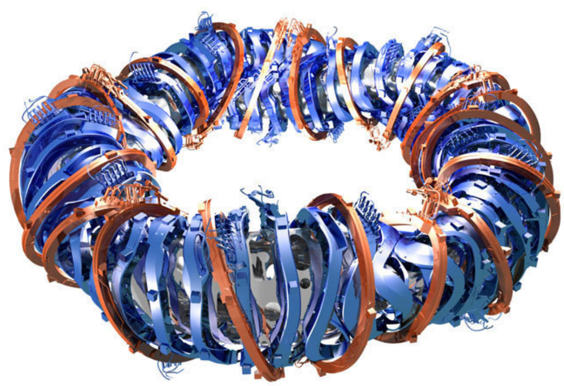

Figure 3.2: Configuration of magnetic coils in the Wendelstein 7-X stellarator *[2]*.

Steady progress has been made in plasma confinement since the 1960s. In Figure 3.3, progress by decade for tokamaks and stellarators is tracked with the help of two parameters. The horizontal axis is the temperature of the ions (mostly, hydrogen ions) in the plasma core. The vertical axis is the product of the density of ions in the plasma (measured in ions per cubic meter) and the confinement time (in seconds). Also shown are the parameters for two important devices at the frontier of current fusion science: ITER and W7-X. Below, we elaborate on temperature, density, and confinement time.

Ion temperature

The ion temperature at the core of the plasma is plotted in Figure 3.3. The temperature is quantified in two ways: 1) as the absolute temperature, in degrees Kelvin (K), which at such high values is trivially different from the temperature in degrees Celsius; and 2) as the energy equivalent of the absolute temperature in thousands of electron volts (keV). 1 keV = 11.6 million degrees Kelvin, as can be confirmed by comparing the two horizontal scales in Figure 3.3. The core ion temperature has marched upward in actual fusion devices by a factor of about 1,000 (from two hundredths keV to 20 keV, or, equivalently, from about 200 thousand degrees to 200 million degrees) over approximately the first 40 years of fusion research. The highest temperatures reached at the end of the 1990s are approximately as large as the temperature goal for ITER. Far more improvement is required for the other variables than for temperature.

The plasma temperatures required for fusion reactors generally cannot be reached without supplementing the energy from the reactor's electric fields with additional energy sources. One strategy is to inject a beam of energetic neutral particles, like diatomic deuterium (D_2), that collide with the plasma's particles and raise their temperature. Radiofrequency heating is also used.

In a plasma, the temperatures of the positively charged nuclei (ions) and the negatively charged electrons can be different when one or the other is being heated or cooled selectively. The ion temperature will exceed the electron temperature when an external beam of neutral particles heating the plasma preferentially heats the ions. The same inequality in temperature occurs in plasmas when electrons cool themselves by emitting radiation; radiation cooling can be one of a plasma's important energy loss mechanisms.

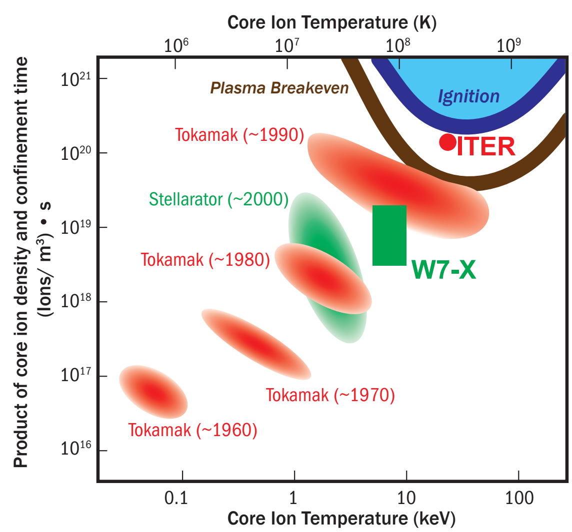

Figure 3.3: Performance of the world's tokamaks and stellarators over the past decades *[3]*. Many devices are included within each oval. The current goals of ITER (a tokamak) and Wendelstein 7-X (W7-X, a stellarator) are also shown. The lower U-shaped band (dark brown) is the approximate region for "plasma breakeven," where as much energy is generated within a plasma as is supplied to the plasma from external sources. The upper U-shaped band (dark blue) shows the "ignition" region, where fusion energy output is sustained without external energy input.

Ion density
Characteristic best values associated with the 1990s tokamaks are a confinement time (see below) of one second and an ion density of $1x10^{20}$ ions per cubic meter, resulting in values of their product near the top in Figure 3.3. The density of atoms in a gas at atmospheric pressure and room temperature is approximately $2.5x10^{25}$ atoms per cubic meter – about 250,000 times greater than this plasma ion density. Doubling the ion density in a plasma results in four times more fusion reactions (since the reactions are encounters of pairs of ions) and thus four times more power is generated in that volume, other things being equal.

Confinement time
The confinement time is a measure of the ability of the plasma to stay hot in spite of thermal losses; the more the energy in the plasma is insulated against these losses, the longer the confinement time. Quantitatively, the confinement time is the amount of energy in the plasma divided by the rate at which energy is being lost from the plasma, which in equilibrium is the same as the rate at which heat is being provided to the plasma to sustain it. The heat can be provided to the plasma either externally or from the energetic helium-4 nuclei produced in the fusion reactions in the plasma, or both ways. The longest confinement times to date have been about one second.

As seen in Figure 3.3, the product of confinement time and ion density improved about 10,000 times during the first era of fusion energy. Some of the lengthening of confinement time was the result of experimental fusion reactors becoming larger. Ions and electrons simply take longer to diffuse to the walls from the center of the plasma in a bigger reactor, other things being equal.

Plasma breakeven and ignition
Figure 3.3 shows, at the upper right, two parabolic bands labeled “plasma breakeven” and “ignition.” A plasma has achieved plasma breakeven when the nuclear energy generated within the plasma is as large as the energy that sustains the plasma from external sources. Ignition occurs when fusion energy can be sustained with no external energy source at all: the energy deposited within the plasma arises entirely from its nuclear reactions. The two bands are U-shaped and the ignition band is displaced directly upward by less than a factor of ten. At the bottom of the U, the product of density and confinement time is smallest, and the core temperature, for both plasma breakeven and ignition, is about 20 to 30 keV. Since increasing the confinement time or the density is difficult, research with the goals of plasma breakeven and ignition has sought to achieve a plasma whose core temperature is near this minimum.

Two tokamaks in the 1990s were fueled with deuterium and tritium and for about one second achieved conditions only slightly below plasma breakeven. ITER’s goal is to generate 10 times as much fusion power as the external power required to sustain the plasma, thereby coming close to achieving ignition. The temperature in the core of the plasma is expected to reach about 20 keV.

Superconducting magnets and pulse duration
Fusion research reactors in the 1990s created fusion power as high as 16 megawatts, but in short pulses – pulses lasting about one second. To achieve longer pulses, superconducting magnets are required rather than ordinary magnets. The distinctive characteristic of a superconducting magnet is that it does not require energy to sustain a magnetic field because the superconducting material exerts no resistance to current flow. At a fusion plant, these savings in magnetic energy would be far higher than the energy for the refrigeration that lowers the magnet temperature to where it is superconducting – close to absolute zero. In addition, superconducting magnets can create stronger magnetic fields for long pulses than ordinary magnets. Several experimental fusion reactors with superconducting magnets are now in operation, including recently built tokamaks in China and South Korea and Germany’s W7-X stellarator. The world’s largest superconducting magnets are heading for ITER, where a fusion output power of 500 megawatts is expected to be sustained for at least 400 seconds.

For every superconductive material, there is a temperature below which the material is superconducting (has zero resistance to current flow) and above which it is no longer superconducting and has finite resistance. The transition temperature depends on the magnetic field in the material: the stronger the magnetic field, the lower the transition temperature. Above some critical magnetic field, the material is no longer superconducting, no matter how low the temperature. For the superconducting materials used today in fusion reactors, the magnets are cooled by liquid helium, which enables the temperature to come close to absolute zero. The two kinds of superconducting magnets being installed at ITER are based on niobium-titanium (NbTi) and niobium-tin (Nb_3Sn) superconductors.

If a superconducting magnet suddenly transitions out of its superconducting state (e.g., by warming up), rapid heating ensues due to the large currents that flow through the magnet. These quenching events represent a potential explosion hazard because of the large amounts of energy they can release *[4]*. However, with modern designs superconducting magnets can be protected against such quenches.

Instabilities

A plasma can have instabilities at a range of scales. Small-scale instabilities cause turbulent transfer of heat from the core to the edge and limit the confinement time. They are nearly always present. Large-scale instabilities can be triggered, particularly in tokamaks, when the plasma's pressure or current density varies too strongly and in too many places within the plasma. Severe large-scale instabilities can drive the hot plasma into a wall and damage the wall, whereupon the plasma becomes too cold to sustain fusion reactions and the reactor shuts itself down. Learning to control and avoid large instabilities is one of the major science frontiers. Figure 3.4 shows the results of high-energy "runaway electrons" hitting a portion of a beryllium tile on an inner surface of the plasma containment chamber at the JET fusion research facility in the United Kingdom. The large electric fields generated during a disruption in a tokamak can generate such electrons. In this case, the damage was created deliberately at the JET research laboratory in the United Kingdom to study the phenomenon.

Fusion energy and nuclear reactions

A "bound" system is any system that requires energy to separate it into its components. The nuclei in nature are bound combinations of neutrons and protons, collectively called "nucleons," and each nucleus has a specific binding energy. The amount of binding of any nucleus, divided by its number of nucleons, is displayed in Figure 3.5, for all nuclei. (Actually, since many nuclei have the same total number of nucleons, what is plotted is either the value for one of these nuclei or some average.) The number of nucleons ranges from one for both the neutron (n) and the proton (^{1}H) to 238 for uranium-238 (^{238}U). Zero is at the top of the vertical scale, and the further down from zero, the stronger the binding per nucleon.

The curve has a U-shape, because the most bound nuclei in nature are near the iron nucleus that has a total of 56 neutrons and protons (^{56}Fe). A nuclear reaction can be thought of as a ball rolling down toward iron from either end of the curve. Starting with nuclei lighter than iron (to the left of iron in the figure), nuclear energy can be released when the protons and neutrons rearrange in new combinations closer to iron; such rearrangements include fusion reactions. Similarly, fission reactions start with nuclei heavier than iron, and they too release nuclear energy by rearrangement of the protons and neutrons.

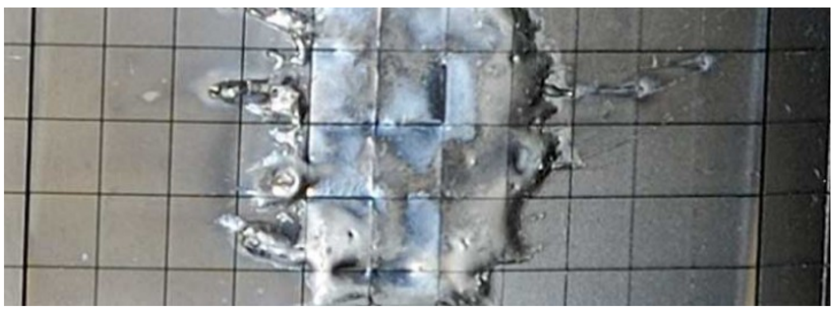

Figure 3.4: A plasma disruption leads to "runaway electrons" striking and partially melting one of the beryllium tiles on a beam protecting the inner wall of the confinement chamber at the JET research facility *[5]*. The thin cut lines on the tile are approximately 12 millimeters apart, and the tile is approximately 50 millimeters deep.

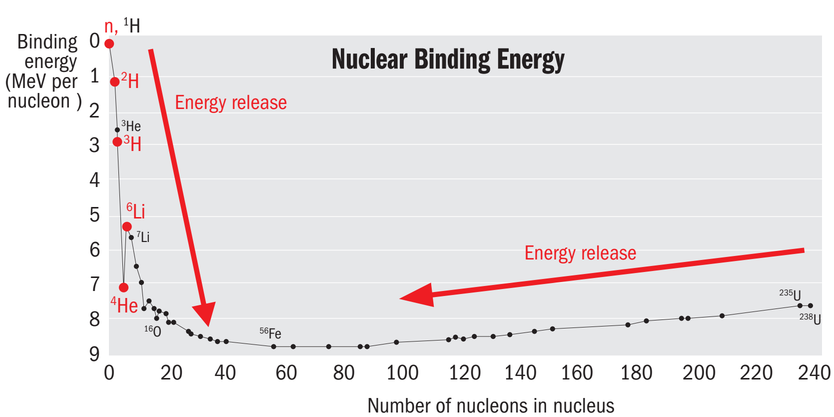

Figure 3.5: "The Curve of Binding Energy" *[6]*: The horizontal axis orders the nuclei in nature by their total number of nucleons (protons and neutrons). The vertical axis is the binding energy per nucleon: the amount of energy required to take apart a nucleus and create separated protons and neutrons, divided by the number of nucleons. The five reactants or products involved in the energy-releasing deuterium-tritium reaction and the tritium regeneration reaction (Reactions 1 and 2 in the text) are in red.

Nuclear reactions for deuterium-tritium fusion

Expanding on the discussion in Article 2, the key nuclear fusion reaction in today's research is:

$$^{2}H + {}^{3}H \rightarrow n + {}^{4}He + 17.6\text{ MeV} \qquad \text{(Reaction 1)}$$

On the left hand side, ^{2}H and ^{3}H are isotopes of hydrogen, also called deuterium (D) and tritium (T) respectively. The two products, a helium nucleus and a neutron, emerge in opposite directions, the neutron carrying away 80 percent and the helium nucleus carrying away 20 percent of the energy released in the fusion reaction. Because the helium nuclei have electric charge, they slow down in the plasma. They cool down to the thermal plasma temperature, primarily by colliding with the plasma electrons and to a lesser extent with the deuterium and tritium nuclei. The energy they transfer to the particles that slow them down heats the plasma. Nearly all of the thermalized helium ash would then be guided out of the reactor, although a small fraction would become embedded in structural materials, eventually damaging them. The neutrons would not be confined by the electromagnetic forces and would travel beyond the plasma retaining their initial energy. Except for the negligible fraction of the neutrons which would decay (neutrons have a 10 minute half-life), every neutron would then be absorbed as a result of a nuclear reaction with some structural material surrounding the core. A very large fraction of the neutrons would be absorbed in the blanket, where the neutron would react with lithium (see Reaction 2 below).

Inspecting Figure 3.5, the two reactants and two products involved in Reaction 1 are found at the far left: the two nuclei entering into the fusion reaction (^{2}H and ^{3}H) are only a little way down, ^{4}He is quite far down, and n at the top (in fact, not bound at all). The exiting combination of n and ^{4}He is a more deeply bound system than the entering combination of ^{2}H and ^{3}H, and the extra binding is what enables the release of energy. Reaction 1 releases an enormous amount of energy: twenty million times more energy is released when a kilogram of deuterium reacts with tritium than when a kilogram of gasoline is burned in air.

Because tritium is radioactive with a short half-life (12.3 years), it is present in only negligible quantities on the Earth and is very expensive to produce. Accordingly, the D-T fusion strategy for commercial energy production presumes that tritium regeneration will be integrated with tritium use and energy production at a single facility. The regeneration is expected to be accomplished by a nuclear reaction between the neutrons produced in Reaction 1 and lithium embedded in the blanket surrounding the plasma. The products of this reaction are tritium and helium. One such tritium-producing fusion reaction is:

$$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He + 4.8\text{ MeV.} \qquad \text{(Reaction 2)}$$

Inspecting Figure 3.5, we see that Reaction 2 also results in a net movement downward towards, on average, a more deeply bound system, so that Reaction 2 also produces energy.

Lithium in nature is a mixture of two isotopes of lithium, ^{6}Li and ^{7}Li. ^{6}Li is less common (in the Earth's crust there are slightly more than twelve ^{7}Li nuclei for each ^{6}LI nucleus), but ^{6}Li is far better at absorbing a neutron and making tritium than ^{7}Li. Accordingly, a future fusion energy system might well include front-end lithium-enrichment facilities to create lithium that is mostly ^{6}Li for use in the reactor blanket.

Summing the energy release from Reactions 1 and 2, 22.4 MeV are released when a deuterium and a Lithium-6 nucleus are consumed and two helium-4 nuclei are produced. Assuming that all of this energy is available for use and that the neutron output from Reaction 1 is the same as the neutron input to Reaction 2, we can estimate the flows of reactants and products for a 1,000-megawatt fusion reactor converting fusion heat into electricity at 40 percent efficiency and running 90 percent of the time. Each year Reaction 1 would consume approximately 80 kilograms of deuterium and 120 kilograms of tritium fuel and would produce 160 kilograms of helium-4 and 40 kilograms of neutrons. Reaction 2 would regenerate the 120 kilograms of tritium from the 40 kilograms of neutrons, while consuming 240 kilograms of lithium-6 and producing another 160 kilograms of helium-4.

Deuterium is not radioactive, and even though it is a rare constituent of hydrogen, there is so much water on the surface of the Earth that it can be considered abundant. In the oceans, approximately one hydrogen nucleus in 6,500 is deuterium, and all the rest are the common isotope (written either ^{1}H or p, for proton). Heavy water is the water molecule with both of its hydrogen nuclei in the form of deuterium, written D_2O. (H_2O is sometimes called "light water.") Heavy water is the principal industrial product containing deuterium. To provide the heavy water for Canadian nuclear fission reactors, the Bruce Heavy Water Plant in Canada (the world's largest heavy water production plant) produced 700,000 kilograms of heavy water per year from 1979 to 1997 *[7]*, or 140,000 kilograms of deuterium per year. This production rate is reassuringly large, in relation to the demand for deuterium for fusion on a commercial scale. Imagine that a central role for fusion in the future global energy system entails the deployment of 1,000 of the 1,000-megawatt D-T facilities described above. Using our estimate of 80 kilograms of deuterium consumption per year for such a plant, 80,000 kilograms of deuterium would be consumed, which would require only one deuterium production plant on the scale of Bruce.

Today, the world has a modest tritium inventory, most of it located in Canada at the Tritium Removal Facility in Darlington, Ontario operated by Ontario Hydro, a Canadian electric utility. This facility was built in the 1980s near one of the utility's nuclear fission plants. The utility at that time operated or was building 20 large CANDU nuclear fission power reactors. In CANDU reactors, tritium is made in much greater quantities than at any other kind of fission reactor, because the coolant is heavy water. Tritium is made in these reactors when reactor neutrons collide with coolant deuterium. On average, each of these CANDU reactors (most of them 600 megawatt plants) was expected to produce about 100 grams of tritium per year, so the Tritium Removal Facility was sized to process about two kilograms of tritium per year and to remove for storage 97 percent of the tritium processed. An estimate published in 2011 reported that the inventory of tritium from CANDU reactors was 20 kilograms *[8]*.

There is a second inventory of tritium in hydrogen bombs. The actual amount is classified, but it has been declassified that each bomb generally has less than 20 grams. Assuming that four grams of tritium are in each hydrogen bomb and that the world has 10,000 such weapons, the world inventory can be estimated at 40 kilograms of tritium. About five percent of the tritium decays each year, so that to keep the tritium inventory constant would require tritium production of two kilograms per year.

Compare both estimates of two kilograms per year to the 120 kilograms of tritium per year consumed in a single one of our representative 1,000 megawatt D-T facilities. The requirements for tritium in a global energy system where D-T fusion power is widely deployed dwarf all current flows of civilian and military tritium.

With fusion power plants that combine burning plasmas and lithium blankets, tritium is expected to be generated at least as quickly as it is consumed. But who will supply the tritium for the very first D-T fusion reactors, if Ontario Hydro's stock is insufficient? Some portion of Ontario Hydro's tritium inventory will decay away – unused, the stock will halve every 12 years. Another portion will be used at ITER. Perhaps the very first fusion devices will be able to be coupled to blankets that produce considerably more tritium than the plasma consumes, so that the tritium inventory can be built up within the fusion program. Perhaps some of the tritium required for the first fusion reactors will be produced in CANDUs or other nuclear fission reactors – at a rate that is deliberately matched to the tritium needed for fusion research and development.

Another potentially relevant nuclear reaction

The combination of Reactions 1 and 2 is not the only path to fusion energy that scientists are investigating. One particular alternative, the "proton-boron-eleven" (p-^{11}B) reaction, is shown in Reaction 3.

$$p + {}^{11}B \rightarrow 3\,{}^{4}He + 8.7\text{ MeV.} \qquad \text{(Reaction 3)}$$

The reactants are a proton and the ^{11}B nucleus, which has five protons and six neutrons. Thus, the reactants, all together, have six protons and six neutrons. The products are three identical helium-4 nuclei, each with two protons and two neutrons.

Fusion power based on the p-^{11}B reaction has two advantages, relative to fusion based on the D-T reaction with tritium regeneration: 1) the p-^{11}B reaction does not consume tritium, thereby avoiding the need for a complex tritium-regeneration system, and 2) the p-^{11}B reaction does not produce neutrons, thereby avoiding the damage to structural materials which neutron bombardment creates. However, the p-^{11}B plasma can sustain the production of fusion energy only at a temperature roughly 10 times higher than the temperature required for the D-T plasma. Sustaining such high temperatures exclusively by fusion generation may not be possible, because such a hot plasma radiates energy away too quickly.

Moreover, no compelling strategy has been identified for removing the charged helium-4 particles from the p-^{11}B plasma while they still carry their initial kinetic energy so that their kinetic energy can be converted to some other form of energy outside the plasma rather than within the plasma. Recall that in the D-T plasma only the electrically neutral particles (the neutrons) carry their kinetic energy beyond the plasma, while the energetic charged helium-4 particles do not leave the plasma and deposit their kinetic energy within the plasma.

Burning plasma

The next two decades of fusion research are expected to reveal, for the first time, the dynamics of a burning plasma – a plasma where the dominant energy source is within the plasma itself. The detailed behavior of a D-T plasma under these circumstances cannot be completely predicted. New sources of instability may appear, and they may or may not turn out to be straightforward to handle.

However, much else about the system in which the D-T plasma will be embedded can be anticipated.

Here we review challenges associated with recycling tritium, recovering the thermal energy in the blanket, and maintaining structural integrity for critical reactor components in spite of incessant neutron bombardment. These challenges are being addressed in many fusion research laboratories and are expected to be a major focus at ITER.

Figure 3.6 shows the flows of fuels and products at steady state in a deuterium-tritium power plant. The figure is intended to represent the system being developed today by the magnetic confinement fusion research community, including for ITER. Within a vacuum vessel are a deuterium-tritium fusion reactor and a tritium-regenerating lithium blanket. The plasma is confined within an inner region whose outer boundary is the first wall of the blanket. Not shown, the vessel has injection ports and is surrounded by magnets.

The positively charged ^{4}He nuclei produced in the fusion reaction lose their kinetic energy in the plasma, while the electrically neutral neutrons escape the plasma but are stopped in the blanket, where they generate tritium and heat. A heat exchanger penetrating the blanket removes heat from the blanket to keep it at constant temperature and transports the heat to a steam or gas turbine, which generates electricity.

There are two critical tritium cycles.

1. *The divertor cycle* In today's deuterium-tritium reactors, only about 2 percent of the deuterium and two percent of the tritium entering the plasma actually react before they are removed from the plasma by a divertor. The "unburned" 98 percent of the deuterium and tritium is then recycled and returned to the plasma. The recycle time is expected to be approximately one hour at ITER.

   The divertor also pumps the helium out of the plasma; otherwise, the helium would dilute and cool the plasma. The divertor also removes other impurities, such as materials ablated from the walls.

2. *The blanket cycle* Tritium is so scarce, tritium production in the blanket must produce at least as much tritium as is consumed in the plasma's core: the blanket must accomplish tritium "breeding." One neutron is produced in the D-T reaction for each tritium nucleus consumed (Reaction 1) and there is at least some chance that this neutron will not enter the blanket and react with lithium. This means that a fusion neutron that reaches the blanket must produce somewhat more than one tritium nucleus. Blankets are expected to embed neutron multipliers to make this possible. One such multiplier is beryllium: when a neutron is absorbed by beryllium, two neutrons are produced. Lead is another neutron multiplier.

   The tritium produced in the lithium blanket must be extracted from the blanket so that it can be injected into the plasma. Tritium extraction is another subject of current fusion research.

   As for the lithium in the blanket, it is assumed not to require replenishment any more rapidly than the rest of the blanket.

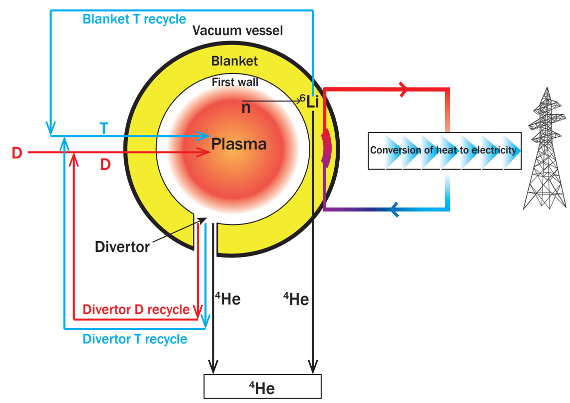

Figure 3.6: Schematic of the materials flows of deuterium, tritium, and helium through a fusion reactor system. *Source:* authors.

Heat extraction

To produce electricity at a fusion power plant, thermal energy in the blanket (the result of Reactions 1 and 2) must be extracted and used to drive a generator. The efficiency of the power plant depends critically on the temperature of the blanket and the efficiency of extraction of heat from the blanket. Heat transfer from the blanket can be accomplished by steam, by a gas such as helium, or by a liquid metal. Both steam and gas heat extraction methods were studied in the European Power Plant Conceptual Study *[9]*. The water-cooled system is less technologically demanding; the maximum temperature in the blanket, 300 degrees Celsius, is similar to the temperature in a pressurized water fission reactor. The conversion efficiency from blanket thermal energy to electricity should be about 30 percent. Advanced blanket systems might absorb the neutrons and regenerate the tritium in a molten mixture of lithium and lead, which would allow blanket temperatures between 700 and 1100 degrees Celsius and efficiencies up to 60 percent.

Materials damage by radiation and plant availability

A large commercial power reactor that operates nearly continuously throughout the year is called a baseload power plant. Many nuclear and coal power plants are baseload plants. Working as intended, they require infrequent maintenance and at a time planned well in advance. For a future fusion plant to be a baseload plant, it will need to minimize unplanned shutdowns and the time required for scheduled maintenance. Accordingly, the durability of components subjected to high levels of neutron radiation is a major constraint on fusion reactor design and materials choice. The two major plasma-facing components of the fusion reactor are especially vulnerable. These are the "first wall" (the innermost surfaces of the blanket) and the divertor. They must be replaced before they lose structural integrity, and such replacements must not be frequent.

The bombardment of structural materials by fusion neutrons displaces atoms from their initial locations in the material's crystalline structure and also drives nuclear reactions at these sites that create helium gas. Both displacement and helium production gradually reduce structural integrity and create embrittlement. Structural damage is quantified by a parameter called "displacements per atom." Steel in a fusion reactor may experience 15 displacements per atom each year (on average, every atom has moved 15 times per year!). These displacements may include later ones that undo the effects of earlier ones by sending an atom back to its original position *[10].*

There is little experience to draw on. Fusion neutrons emerge from the fusion event (Reaction 1 above) with about seven times the average energy of fission neutrons, so even the neutron damage in fission reactors is only partially relevant. The joint European-Japanese International Fusion Materials Irradiation Facility (IFMIF) is expected to have the capability to begin to fill this gap in knowledge.

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Article 4: Economics

Understanding the economic potential of fusion energy is a complex challenge since fusion is still many years from being a market option. Uncertainties abound at multiple scales, from the power plant to the full global energy system.

This article has two parts. In the first part, we consider the determinants of the cost of electricity from an individual fusion power plant. In the second part, we investigate how fusion will compete for energy market share. We limit our discussion to magnetic confinement fusion, and more particularly to its tokamak configuration.

Estimates of the cost of fusion electricity

The cost of fusion electricity is driven principally by its capital cost and by how many hours the plant can run each year. Quantitative discussion focuses on "the levelized cost of electricity." In essence, the levelized cost is the total cost of building a plant and running it over its lifetime, divided by the kilowatt hours of energy that the plant produces over its lifetime. Like its fission counterpart, the total cost of a fusion power plant is dominated by its initial capital costs. The kilowatt hours produced over its lifetime are affected primarily by the size of the plant, the number of hours that it is able to run each year, and the efficiency with which the thermal energy produced through fusion is converted into electricity.

There are many estimates of the capital cost of a fusion plant *[1,2,3,4]*. The estimates range from $2,700 to $9,700 per kilowatt of capacity. The plants have a capacity between 1,000 and 1,500 megawatts. Assuming that the capital cost per kilowatt is roughly independent of the size across this small range of sizes, the estimated capital cost of a fusion power plant with 1,000 megawatts of capacity would range from 2.7 to 9.7 billion dollars. (Costs throughout this article are in 2010 US dollars *[5]*).

The wide range of capital costs is partially explained by varying assumptions about how many plants of the same kind have been built prior to the plant whose cost is being estimated. Fusion plants are expected to become less expensive as more plants of a specific design are built. "Technological learning" captures this issue: cost models often assume that costs will fall at some well-defined rate as additional units of the same kind are installed.

The wide range of costs is also due to differences in the assumed technological maturity of the plant. Fusion plants are likely to become less expensive as they incorporate successive advances in technology. For example, with maturity may come greater efficiency in converting the thermal energy of fusion into electricity. Nearly a factor of two is at stake, with conversion efficiency ranging between 30 and 60 percent. This efficiency depends especially on the temperature of the blanket; the blanket absorbs the thermal energy released in the fusion reactions and delivers most of that thermal energy to the turbine that produces electricity. The larger the difference between the temperature of the blanket and the temperature of the environment (ocean or river water, for example), the higher the efficiency of electricity generation. Efficiencies of 30 percent are representative when the blanket is water-cooled and maintained at a temperature of 300 degrees Celsius, so that steam enters the steam turbine at nearly 300 degrees Celsius. The higher 60 percent efficiency might be realized if a blanket could be maintained at much higher temperatures as a result of being cooled by a gas or a liquid metal.

Two kinds of costs are associated with any power plant: the capital cost for building the plant (incurred in its first years) and the cost of running it (for many further years). To combine these costs into a complete cost per year that can be used to calculate cost of electricity requires "annualizing" the initial capital cost, meaning transforming it into a cost per year to match the units of the costs of running the plant. Typically, this is done by multiplying the capital cost by some factor (in units of percent per year). A typical multiplier is 15 percent per year, which not only transforms the capital cost into a cost per year, but also incorporates the associated costs of borrowing money, depreciation, insurance, and taxes. Using this multiplier, if the capital cost for building a 1,000 megawatt plant is six billion dollars, the annualized cost will be 900 million dollars per year, or 900 dollars per year per kilowatt of plant capacity. If the plant were to operate continuously over all the 8,760 hours in a year, the cost per kilowatt-hour associated with the capital cost alone would be approximately ten cents.

However, plants do not run continuously for a whole year; if the plant ran only half the year, the capital component of the cost per kilowatt-hour would be twenty cents. Accordingly, another source of variation in cost estimates is the assumption about the number of hours that the plant runs each year. A capital-intensive technology like fusion generally requires nearly full-time operation to be competitive. Unique

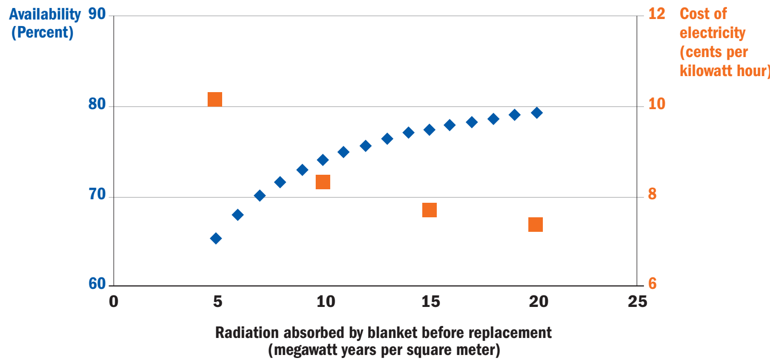

Figure 4.1: The dependence of fusion power plant availability and the cost of fusion electricity on the durability of the fusion blanket *[7]*. The durability of the blanket is quantified as the maximum amount of absorbed radiation (in megawatt-years) that the blanket can tolerate per square meter of blanket surface area. The more radiation the blanket can absorb before replacement, the fewer the periods during which the power plant is shut down for blanket replacement and the lower the cost of electricity.

in its significance for fusion plants is "scheduled component replacement," which will affect its availability. Critical components degrade and need to be replaced many times over the lifetime of the plant as a result of the wear and tear that they sustain from irradiation by fusion neutrons and charged particles.

Accordingly, the fusion research community pays close attention to the replacement of parts that lose their function after only a few years. The most important areas of the plant, from the perspective of durability, are those in close proximity to the fusion plasma itself, notably the first wall, the blanket, and the divertor. One current estimate indicates that divertor replacement could take four months and divertor replacement in combination with blanket replacement could take six months. Every replacement would also require a one-month cooling period at the front end and a one-month conditioning period at the back end before the plant could produce power *[6]*.

Thus, there is an important relationship between durability of components requiring replacement and the cost of fusion electricity. Figure 4.1 shows the benefit obtained when a blanket is able to withstand a larger amount of radiation before replacement. Consider the durability of the blanket for two values of the total tolerable neutron absorption before blanket replacement is required: five and 20 megawatt-years of absorption of neutron irradiation per square meter of surface. This four-fold increase in durability is seen to produce an increase in power plant availability from 65 percent to 80 percent and a fall in the total cost of a kilowatt-hour from ten cents to seven cents. The cost curve has diminishing returns: at high durability, further blanket durability has diminishing benefit, as other factors (such as divertor replacement) become the more important causes of shutdowns.

A priority for fusion, therefore, is the development and demonstration of materials that will tolerate the fusion environment for a long period. The development of analogous materials has enabled a well-operated fission plant to run roughly 90 percent of the time, with a single shutdown period roughly once a year. The most difficult component to replace in a fission plant, the pressure vessel within which the fissions occur, is expected to remain intact for the lifetime of the plant. However, the neutrons from fusion are more energetic than those from fission and do more damage.

Figure 4.2 shows the allocation of the total cost of fusion power reported in the European Power Plant Conceptual Study *[1]*. A similar analysis is found in the U.S. Advanced Research, Innovation, and Evaluation Study *[2]*. The European study investigates four variants of fusion plants, but only Model A, the variant described as requiring the least amount of new technology, is shown in Figure 4.2. The cost estimates are based on a "tenth of a kind" plant, meaning that these are the costs for the tenth plant of a similar kind – lower costs than the costs for the first plant because some technological learning has occurred. The capital cost is estimated to be $9,700 per kilowatt of capacity, the discount rate is 6 percent, there is no taxation, the plant lifespan is 40 years, the plant is expected to run 75 percent of the time, and efficiency of conversion of fusion power to electricity is 31 percent.

With these assumptions total costs can be grouped, and shares for each group can be estimated: Capital (73 percent), Divertor Replacement (12 percent), Blanket/First Wall Replacement (4 percent), and Operation and Maintenance (9 percent). Note that the combined cost for the replacement of the divertor and the blanket's first wall is 16 percent of the total cost. Other costs, mainly the costs of fuel and decommissioning, are reported as being negligible. The cost of handling the regenerated tritium is presumably placed in the Operation and Maintenance category, since it is a recurrent cost. The same study reports that the largest contributions to the total capital cost are 1) the combined cost of the magnets and cooling system, and 2) the combined cost of buildings and site preparation.

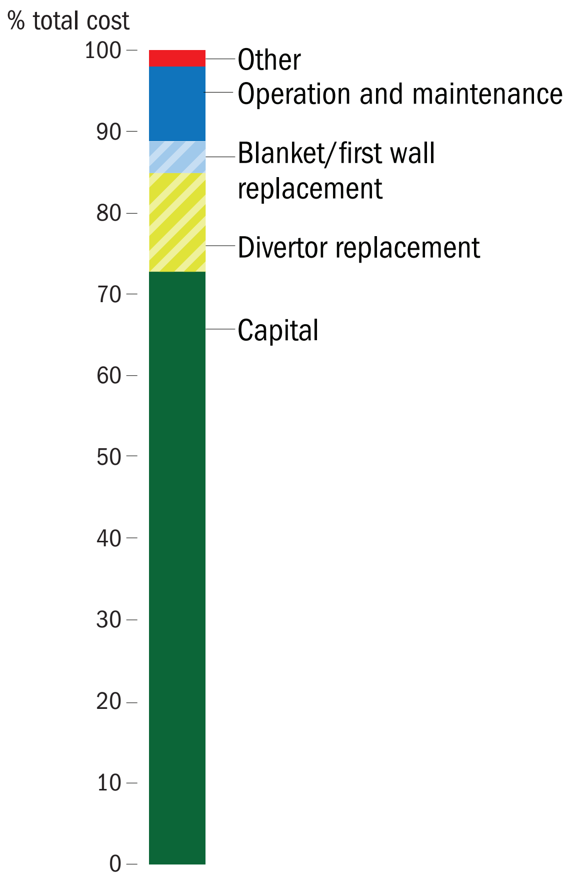

Figure 4.2: Components of the total cost of electricity produced by a fusion power plant based on a tokamak reactor, shown as a percent of total cost *[1]*.

We draw five key messages from this section:

1. There is a wide range of estimates for the cost of electricity from future fusion power plants.
2. Uncertainty regarding in what directions and how rapidly technology will advance is a key contributor to this range.
3. For all these estimates the primary determinants of the cost of electricity are capital costs and the proportion of time that the plant can operate.
4. Capital costs are dominated by the costs of the magnets and cooling system.
5. The proportion of time a plant can operate is mainly determined by how often the first wall, blanket, and divertor need to be replaced.

While higher-level modeling of fusion energy's future economic competitiveness (such as the market share study described immediately below) can provide an orientation to fusion's potential role in the global energy system, the deep uncertainty about fusion's likely future cost implies that all quantitative economic estimates emerging from these models are highly speculative at this stage.

Fusion's market share in the 21st century

The prospects for fusion energy as a source of electricity over the coming century will depend not only on fusion's own future costs but also on the future global electricity market. The size of that market depends on the rate of economic growth, the amount of electrification of the energy system, and the efficiency with which electricity is used to provide goods and services. Since fusion is a low-carbon energy source, its future role in the market also depends on the extent to which concern for climate change is translated into carbon policies that disadvantage high carbon energy sources (the fossil fuels: coal, oil, and gas) relative to low-carbon sources. Also significant are the costs of other low-carbon sources relative to the cost of fusion.

Little modeling of the impact of fusion on energy markets has been done, largely because cost estimates for fusion are so uncertain, as demonstrated in the previous section of this article. We report one of the few modeling studies where fusion costs and related economic parameters (such as the time of fusion's arrival) are assumed and fusion's impact on the full global energy system is developed *[8,9]*. We provide quantitative results from this study that illustrate some of the factors that can influence fusion's future market share. The exact model results are unimportant relative to its qualitative conclusions, which are consistent with other work *[3,10,11,12]*.

The researchers used one of the best-known integrated assessment models, known as GCAM, developed and maintained at the Pacific Northwest National Laboratory of the U.S. Department of Energy. The model's inputs include the performance of the economy, carbon-cycle science, climate policy, and the costs of competing energy technologies. Its outputs are representations of future energy markets in 14 geopolitical regions every five years from 2015 to 2095. At each time step, the demand for electricity is met by a broad array of energy technologies.

Although the model can describe the entire energy system, here we focus on the electricity sector, where the model calculates electricity prices, carbon prices (carbon taxes), and electricity demand. The study we are reporting adds fusion to the list of electricity-generating competitors that GCAM has modeled previously. The key assumptions for fusion power are the following:

1. *Timing* The model's base case assumes that the first fusion power plant becomes available in 2035, at least ten plants are operating in 2050, and at least 100 plants are on line in 2065. This ambitious schedule is hard to reconcile with the current schedule for ITER and follow-on research projects (see Article 6).
2. *Cost* The median capital costs fall as fusion deployment grows over time. The capital cost of the initial plant is $6,000 per kilowatt of capacity, which is within the range of capital cost estimates discussed above. The unit cost is assumed to fall as additional units are built, as may be appropriate for an immature technology. The unit cost in 2065 is $3,800 per kilowatt, and costs continue to fall moderately after that.
3. *Availability* The plant is assumed to run 90 percent of the time. This would require that the plants achieve shorter shutdown periods for the replacement of irradiated reactor components than is currently expected (see the first part of this article).

The overall optimism in these assumptions suggests that these GCAM model runs probably overestimate the market share of fusion at various future dates. However, the qualitative results from these model runs are instructive, especially those that reveal the dependence of fusion's market share on alternative policy environments. These results reveal the importance of the assumed costs for two of fusion's main low-carbon competitors: carbon dioxide capture and storage (CCS) and nuclear fission. They also show the strong dependence of fusion market share on the price imposed on carbon dioxide emissions to the atmosphere.

In CCS power plants, a fossil fuel or biomass is burned and the carbon dioxide emissions from combustion are "captured" – prevented from escaping to the atmosphere. The carbon dioxide is then "stored," typically, deep below ground in a porous saline geological formation. The first CCS plants are now running. GCAM allows alternative constraints to be placed on the maximum amount of carbon dioxide storage space available below ground in each geopolitical region.

As for fission, its median capital cost for the baseline case in 2065 is $2,700 per kilowatt, about 30 percent less than the corresponding 2065 capital cost for fusion. An alternative in the model is a "low" fission case where in 2095 fission is more expensive (about 30 percent more expensive than the baseline case), which closes the gap between the costs of fission and fusion.

GCAM, for all cases, also restricts the contributions of wind power and solar power to reflect their intermittency.

Fusion competes with 14 other electricity production technologies to meet electricity demand. Three options are carbon-emissions-intensive: power from coal, natural gas, and oil without CCS. The other 11 options are low-carbon – low-carbon rather than zero-carbon because of the carbon dioxide emissions associated with construction of the plant and other ancillary factors. Biomass-based electricity without CCS is one of these. Another four are CCS options, differing in their fuel: coal, natural gas, oil, and biomass. The remaining six are nuclear fission, geothermal energy, hydropower, wind, ground-based solar, and rooftop solar. The market shares of all 15 production technologies from 1990 to 2095 are shown in Figure 4.3 for two representative GCAM scenarios (the original study explores many more scenarios).

Panel I shows Scenario I, the base case and the point of departure for the analysis. Circumstances are unfavorable for fusion because there is no climate policy (no carbon price); all of fusion's competitors, including fission, have their baseline costs; and (not actually relevant, because without a carbon price CCS cannot be viable) there is ample space below ground to store carbon dioxide. Efficiency in electricity use has limited impact: global electricity demand, which in 2010 was approximately 22 trillion kilowatt-hours (a trillion is a million million, or 10^{12}), rises to 90 trillion kilowatt-hours, more than four times the 2010 value, in 2095. Coal power dominates electricity supply in 2095 with 29 percent market share, followed by natural gas and nuclear fission, each with 18 percent. The shares of wind and ground-based solar are seven and five percent respectively. Fusion's share is four percent, or four trillion kilowatt-hours.

How many fusion power plants would be operating in 2095 in Scenario I if fusion actually were to produce four trillion kilowatt-hours that year? Assuming a representative plant that has a capacity of 1,000 megawatts (one million kilowatts) and runs 8,000 hours per year (approximately 90 percent of the time), the plant would produce eight billion kilowatt-hours each year. Thus, the answer is that approximately 500 fusion plants would be operating in 2095 in Scenario I. This is approximately the scale of nuclear fission power today.

Panel II presents Scenario II, a far more favorable case for fusion, where there is significant climate policy, a cost penalty for nuclear fission, and limits on available carbon dioxide storage space. Climate policy is assumed to take the form of a concentration of

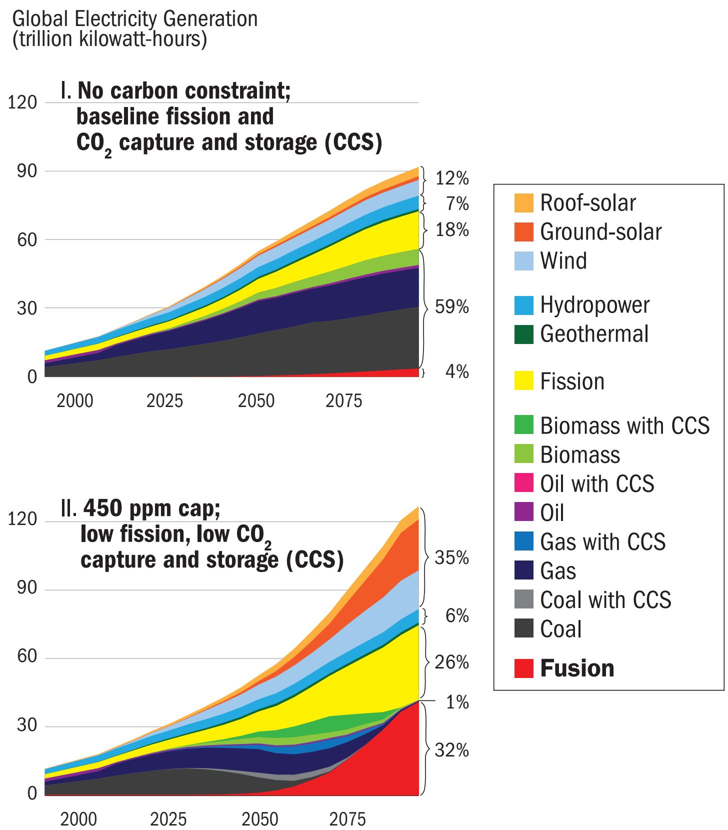

Figure 4.3: Production of global electricity in the 21st century, by source, when fusion is an option ***[8]. Panel I (above):*** **Scenario I, a case unfavorable to fusion because there is no carbon policy and both fission and carbon dioxide capture and storage (CCS) options are fully available.** ***Panel II (below):*** **Scenario II, a case favorable to fusion because there is a 450 parts per million (ppm) climate target and fission and CCS options are constrained. The numbers at the right (in percent) are the shares of total electricity production in 2095 for five bracketed power sources; from top to bottom, these are intermittent renewables, non-intermittent renewables, nuclear fission, fossil sources with and without CCS, and nuclear fusion.**

carbon dioxide in the atmosphere not to be exceeded at the end of the century. Within GCAM there is a carbon cycle model which links carbon dioxide concentrations to carbon dioxide emissions and thereby limits emissions. Emissions reductions are achieved by a globally uniform price on carbon dioxide emissions, which improves the competitiveness of low-carbon energy relative to fossil fuels.

In Scenario II the global energy system is constrained by the requirement that the maximum carbon dioxide concentration in the atmosphere must never exceed 450 parts per million (ppm). (When the concentration is 450 ppm, 450 carbon dioxide molecules are present in every million molecules of air.) This constraint is one of the most common climate policy objectives in the modeling literature *[13]*. A 450 ppm cap is estimated to have a 50 percent chance of limiting the rise of the average surface temperature of the Earth to two degrees Celsius relative to its temperature 200 years ago, thereby potentially avoiding some of the dangerous impacts of climate change. The current concentration is already about 400 ppm. By comparison, the carbon dioxide concentration in 2095 for Scenario I is 810 ppm, roughly double the concentration today. Scenario I assumes that no climate policy is enacted; specifically, throughout the 21st century there is no price on carbon dioxide emissions to the atmosphere. By contrast, in Scenario II a carbon price is imposed that grows throughout the century and reaches more than $280 per ton of carbon dioxide in 2095.

Comparing Scenarios I and II reveals that total electricity demand in 2095 is even higher in Scenario II than in Scenario I. Global electricity consumption in 2095 is 120 trillion kilowatt hours for the 450 ppm climate target, versus 90 trillion kilowatt hours when there is no climate target. The climate target pushes the energy system toward electricity and away from the direct use of fuel – for example, toward electric vehicles and electric space heating.

Fusion's market share in 2095 is eight times larger in Scenario II (32 percent) than in Scenario I (four percent). In Scenario II fusion is the dominant supplier of electricity in 2095, providing 41 trillion kilowatt hours, or ten times as much electricity as in Scenario I. Since we estimated that the fusion output in Scenario I would require 500 representative fusion power plants, it follows that in Scenario II 5,000 of these plants would be operating.

But the differences between the scenarios extend well beyond fusion. Electricity from fossil fuels and biomass provides 59 percent of global electricity when there is no carbon policy, but only one percent when a 450 ppm target is met. In the presence of the climate target, fusion, intermittent renewables, and fission all increase their market share to make up the difference, gaining 28, 23, and 8 percentage points of market share respectively. The gain in fission's share happens in spite of its higher cost in Scenario II than in Scenario I. Scenario I never uses CCS technologies, because there is no price on carbon.

In Scenario II, CCS versions of biomass power plants and (to a lesser extent) natural gas power plants play a significant role in the middle of the century but by 2095 they no longer contribute, presumably because carbon dioxide storage costs have risen as the regional storage sites have filled up.

In summary, as with any similar study, the results reported here are strongly dependent on the assumptions. The results are sensitive to the date of the first commercial plant and its initial cost, the rate of fall of unit cost through learning, and the competitors' costs and constraints. Notably, the costs of fission and fusion are assumed to be similar. Nonetheless two of the study's results are broadly relevant. First, without a carbon target and in the absence of any explicit penalties on fusion's competitors, fusion's share of electricity at the end of the century is small, if it competes at all. Second, the combination of a carbon target and restraints on fission and CCS increases fusion's market share dramatically.

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Article 5: Fusion and Fission

Nuclear fission power has been under serious scrutiny throughout the decades-long history of civilian fission reactors. A complex regulatory system has emerged, accompanied by sizeable public distrust in four areas: nuclear weapons proliferation, the disposal of radioactive waste, reactor accidents, and terrorist or military attack. Fusion power will probably need to deal with the same challenges and fears. But to what extent are the risks from fusion and fission power similar? In order to answer this question, we explore the qualitative and quantitative differences between fusion and fission technology for these four issues. For the most part, we restrict the discussion to magnetic confinement fusion.

Nuclear weapons proliferation

There are two types of nuclear weapons: Fission bombs ("atomic bombs") harness the energy released in fission reactions; the Hiroshima and Nagasaki bombs were fission weapons. A few years after fission bombs were developed, the energy from fusion reactions was harnessed for weapons by using the energy from a fission bomb to set off secondary fusion reactions. These "hydrogen bombs" were even more destructive than fission-only weapons. At the moment, nine countries possess atomic bombs: the U.S., Russia, China, the United Kingdom, France, Israel, India, Pakistan, and North Korea. The first five – and probably Israel and India as well – also have hydrogen bombs, while Pakistan and North Korea probably do not.

Nuclear proliferation refers to the development of nuclear weapons capabilities in new countries. It requires access to special nuclear materials, which the expansion of nuclear power plants could potentially provide. It also requires specialized training in nuclear technology, some of which would be gained through experience with nuclear power.

Civilian fission power is tightly linked to fission weapons through two special materials: plutonium and highly enriched uranium. Either can sustain an explosive chain reaction. The uranium found in nature cannot be used for weapons without expensive manipulation, called isotope enrichment. Isotope enrichment, in which the ratio of uranium-235 to uranium-238 is increased relative to the ratio found in nature, is part of the preparation of uranium for most kinds of nuclear power plants. "Weapons-grade" uranium is produced by further enrichment. Plutonium is found in nature only in trace amounts so it needs to be made in nuclear facilities. Plutonium is a by-product of the reactions in fission power plants, but it is unavailable for weapons use unless steps are taken to separate it from the highly radioactive "spent fuel" in which it resides.

Thus, fission power represents a step toward the nuclear materials for an atomic bomb, but the next steps are not inevitable. There is technological space for civilian fission power without nuclear weapons, and many countries have chosen to be in that space. Because of the requirements for nuclear power, they have nuclear scientists and nuclear equipment, but they do not have and do not seek to have the required separated plutonium or enriched uranium these weapons require. Without these materials no bomb can be built.

The relationship between civilian fusion power and hydrogen bombs is more complicated. First, a country that chooses not to develop fission weapons cannot develop fusion weapons because hydrogen bombs require fission as well as fusion. Second, however, both uranium and plutonium for weapons can be produced at a fusion plant using the abundant neutrons generated in the reactor. Plutonium can be produced at a fusion plant by placing natural uranium just outside the reactor core and bombarding it with neutrons from the fusion reactions. In the same way, uranium-233 of high isotopic purity, a weapons material, can be generated from neutrons bombarding thorium. No uranium enrichment plant would be necessary. Diverting some of its neutrons, a 1,000 megawatt fusion plant could conceivably create enough uranium-233 or plutonium for one fission bomb within a week, not including the time needed to put the necessary hardware in place, which could add a few additional weeks to this proliferation scenario *[1]*.

It would be difficult to disguise the generation of plutonium or uranium-233 if an international safeguards regime with inspections were operating, because a country which operates only fusion plants would have no valid reason to have uranium or thorium on hand. This has been called "the major nonproliferation advantage" of fusion power plants *[2]*. This advantage would not apply to any "fusion-fission hybrid" – a power plant designed to combine elements of fusion and fission reactors.

Having a fusion reactor could conceivably abet a country's transition from fission weapons to follow-on fusion weapons because the fusion reactor could produce tritium for such weapons. Tritium is a heavy isotope of hydrogen that scarcely exists in nature because its half-life is 12 years. Fusion power plants both consume and produce tritium, and if tritium were to become a more common article of commerce thanks to the fusion power industry, this might slightly lower the barriers to fusion weapons.

A larger barrier than tritium availability is the highly guarded secrets related to hydrogen bomb design. But the prospect of fusion power raises concerns here too, at least with regard to inertial confinement fusion, where there is a significant overlap between the technology for pellet compression and ignition and hydrogen bomb design. It is telling that the primary objective of the National Ignition Facility, the main focus of U.S. research in inertial confinement fusion, is to better understand the physics behind thermonuclear weapons without testing them. A particular concern is that scientific data from inertial confinement fusion research could be used in the development of nuclear weapons *[3]*, although the civilian fusion power plants themselves are unlikely to be useful in this regard *[2]*. Magnetic confinement fusion, by contrast, has been the poster child of international collaboration in scientific research, dating back to Soviet collaboration with Western countries in the 1950s – in part because there is no credible pathway from magnetic confinement fusion to nuclear weapons.

Waste disposal

In nuclear fission reactions the uranium nucleus splits into two other nuclei. These nuclei include radioactive isotopes with half-lives ranging from fractions of a second to millions of years. One important radioactive byproduct from the perspective of public health is iodine-131 (half-life, eight days). The human body concentrates any iodine intake in the thyroid gland, and when the iodine is radioactive (which it normally is not) the result, especially in children, can be thyroid cancer. Other damaging isotopes have half-lives of years to decades (cesium-134, cesium-137, and strontium-90); these isotopes dominate the environment months to decades after any fission-reactor accident. The accident at Fukushima Daiichi in Japan in March 2011 led to land contamination by radioactive cesium and the relocation of more than 100,000 people, some of them permanently.

Fission plants also inevitably produce radioactive "transuranic" elements (elements heavier than uranium). Transuranic elements are found in nature only in trace amounts, but they are produced in reactors by a succession of nuclear reactions initiated by the absorption of a neutron by uranium. (When a neutron strikes a nucleus of uranium, the result can be either fission or absorption.) Several transuranic isotopes have half-lives of centuries to millions of years, and these represent one of the most challenging aspects of radioactive waste management for fission power.

Current national regulations for nuclear power require that human beings living thousands of years from now should experience only minimal damage from any radiation created by nuclear energy today. The United States, for example, has targeted 10,000 years or even longer as the minimum duration for geological storage of what is called "high-level" nuclear radioactive waste at the proposed storage facility at Yucca Mountain, Nevada. Such regulations raise deep questions. The regulations governing the Yucca Mountain facility note that "except for a few archaeologic and natural analogs, there is a limited experience base for the performance of complex, engineered structures over periods longer than a few hundred years" (10 C.F.R. § 63.102(h) *[4]*). To date, despite a number of test projects, no permanent facility for civilian high-level waste has become operational. All civilian high-level fission waste is being held in temporary storage, awaiting a long-term solution. A waste facility for military waste is operating in the United States in New Mexico – the Waste Isolation Pilot Plant. Advanced reactors are being considered which may be able to destroy most of the long-lived transuranic isotopes – but, in exchange, radioactive isotopes with shorter half-lives would be generated in abundance and would present their own management issues.

Irradiation of the structural materials of a nuclear fission reactor adds to the radioactivity it produces. Most of this waste is "low-level" radioactive waste, whose storage management is less daunting. United States nuclear regulations allow low-level waste to be buried in relatively shallow trenches. Required storage times for low-level waste can still be as long as 100 years. As a result, even wastes classified as "low-level" present substantial institutional challenges.

A fusion power plant is a radioactive environment for two principal reasons: 1) tritium is inserted into the plasma, regenerated in the blanket, and held in storage before being reinserted into the plasma, inevitably with some losses along the way that end up in waste streams; and 2) materials surrounding the plasma are made radioactive by bombardment by fusion neutrons.

The physical half-life of tritium is 12.3 years, meaning that after 12.3 years half of any tritium initially present has transformed itself into innocuous, non-radioactive helium-3. This twelve-year half-life is short enough that tritium management does not require costly and politically complex long-term storage; 99 percent is gone in 82 years. Moreover, the energy released when a tritium nucleus decays is small relative to most radioactive nuclei. Nonetheless, tritium is subject to intense regulation, because being a heavy isotope of hydrogen, it acts chemically like ordinary hydrogen. In particular, it is readily incorporated into water and can thus be ingested by organisms. Tritium's biological half-life – the time it takes for half the tritium to be eliminated from the human body after ingestion – is about ten days, the same as for water, because essentially all of the tritium is in the form of tritiated water, HTO. Thus, it would take just over two months for a person to eliminate 99 percent of the tritium ingested. (The biological half-life, to be sure, varies from person to person; it can be shortened by drinking large amounts of water.) Releases to the environment and worker exposure are highly regulated; for example, the maximum concentration of tritium in drinking water supplies allowed by the U.S. Environmental Protection Agency (EPA) is just 2 trillionths of a gram per liter of water. Accordingly, the management of on-site tritium is already a preoccupation of operators of fusion research facilities. It will be a central concern at any commercial fusion reactor.

The world's largest civilian facility for tritium processing is the Ontario Hydro's Tritium Removal Facility in Darlington, Ontario, Canada (see Section 3). The facility is on the shore of Lake Ontario and about one hour from Toronto. It processes tritiated water (HTO) whose initial concentration of tritium was 750 million times larger than EPA's allowed concentration in drinking water supplies and whose final concentration after treatment (97 percent tritium removal) was 20 million times larger *[5]*.

As for the generation of radioactivity by neutron bombardment of structural materials, this may well be a larger issue for a fusion plant than for a fission plant. About five times as many neutrons are created in a deuterium-tritium fusion reactor as in a fission reactor producing the same amount of energy, and the neutrons made in the deuterium-tritium reaction carry about seven times as much energy as the neutrons (on average) created in a fission event. The search for better structural materials for fusion reactors, although principally concerned with finding materials that retain their strength under neutron bombardment, also seeks materials whose demands on waste disposal are reduced *[6]*.

It may be possible, at some additional cost, to lessen waste disposal costs by avoiding steels that contain niobium and molybdenum. Neutron bombardment of niobium will create niobium-94 (^{94}Nb), a radioactive isotope with a half-life of about 20,300 years. This half-life is approximately the same as the half-life of plutonium-239 (24,100 years), which is the isotope whose half-life set the scale for the storage of high-level waste from nuclear fission reactors half a century ago. On the other hand, niobium is one of the elements in superconducting magnets (see Article 3), and this raises the question of the extent to which neutrons can make their way beyond the vacuum vessel to the surrounding magnets to generate ^{94}Nb in significant quantities.

As for molybdenum, neutron bombardment creates radioactive molybdenum-93 (^{93}Mo) from molybdenum-92 (^{92}Mo), a stable isotope of molybdenum constituting 15 percent of the molybdenum in the Earth's crust. The half-life of ^{93}Mo is 3,500 years, not a desirable half-life from the perspective of waste disposal. Molybdenum provides resistance to wear and extra strength at high temperatures, so metallurgists would rather not remove molybdenum from steel. Under consideration is the use of an isotope-separation process to provide specialty molybdenum for fusion reactors that contains negligible amounts of ^{92}Mo, thereby essentially eliminating ^{93}Mo from the reactor's structural materials at time of disposal while enjoying the improvements in performance that molybdenum brings to steel *[7]*.

The volume of activated material generated at a fusion power plant would be very large. In the European Union's Power Plant Conceptual Study, it was estimated that over 70,000 metric tons of waste would be generated during the 25-year lifetime of a 1,500 megawatt plant, with another 50,000 metric tons coming at decommissioning *[8]*. If all this waste were considered low-level waste, it would need to be stored for about 100 years *[8]* – a substantial advantage when contrasted with the much longer period required for high-level fission waste. Estimates of the cost for storing low-level waste range from $100 to $10,000 per cubic meter and depend strongly on the radioactivity level. Moreover, the direct payment for storage is estimated to represent only about 15 percent of the total disposal cost; other expenses include evaluation, packaging, and transportation *[9]*.

An alternative to storage as low-level waste, called "clearance and recycling," is being explored *[10,11,12]*. This system would begin with the separation of tritium from irradiated structural components removed from a fusion plant either at the end of their useful lives or when the plant itself is decommissioned. The waste would then be stored for a "decay period," after which materials would have lost enough of their radioactivity through decay to be fit for release and sale into the general economy. For example, concrete from the structure could be crushed and used in road construction. Materials whose radioactivity remains above legal limits would be refabricated into new parts for use within the nuclear industry. Only 10 percent of the waste from the plant would be ineligible for clearance and recycling *[8]*. With further work to identify materials that do not become highly activated or that quickly shed their radioactivity, even further reduction in the burden of fusion waste management might result.

There are already a few examples of clearance and recycling for activated waste from fission reactors. In one instance, 100 tons of lead casks from the Idaho National Engineering & Environmental Laboratory were recycled into bricks for a radioactivity-shielding wall at Idaho State University. The laboratory gave the bricks to the university for free and realized savings of $0.70 per pound by recycling instead of disposing of the waste; moreover, the university avoided buying lead bricks at a cost of about $1.75 per pound *[13]*. However, as of 2008, one review found there had been only five instances of clearance/recycling from fission reactors *[14]*.

The implementation of a clearance and recycling system for fusion power plants would confront serious obstacles. For example, the waste would need to be remotely dismantled, handled, and remanufactured; some of the needed techniques could be borrowed from the fission power industry, but new methods would need to be developed. There would also need to be a market for cleared materials. As one analysis observes: "the American scrap metal industry is highly concerned about radioactivity in their products as consumers may refuse to purchase products they believe are tainted" *[9]*. Even if cleared materials are not avoided out of fear, they will not be accepted if they are more expensive than alternative products that already exist. Finally, the possibility that regulations about radioactivity management could become stricter over time introduces further uncertainty into the clearance and recycling process *[9]*.

In summary, fusion's principal advantage over fission from the perspective of radioactive waste management is the absence of the long-lived radioactive isotopes that are inherent in the fission process. Tritium is the most important radioactive isotope intrinsic to deuterium-tritium fusion, and its in-plant management and releases to air and water are subject to demanding regulations. Tritium has a half-life of only 12 years, so it is not subject to the rules for millennial-scale storage of high-level radioactive waste that currently hobbles fission power. Moreover, there may be opportunities to develop fusion reactor materials that reduce the waste management challenges associated with activated products, thereby compensating for the greater energy of fusion neutrons relative to fission neutrons. (More energetic neutrons create greater transformation of the nuclei in structural materials into radioactive forms.) Nonetheless, the management of radioactive fusion wastes will not be a trivial matter by any means.

Reactor accidents

A "meltdown" occurs at a fission reactor when the reactor's cooling system fails and the core's highly radioactive contents provide, after several hours, sufficient heat to melt the core's containment vessel, whereupon the radioactive contents can move to the floor of the reactor and beyond. The Fukushima Daiichi accident in Japan, following a large earthquake and tsunami, produced a meltdown at several of the reactors. Seconds after the earthquake, the systems designed to shut down the reactors worked as intended and halted fission reactions. However, the reactor's backup cooling systems – needed to control the residual decay heat from the fission products in each reactor's core – failed when a tsunami a few minutes later sent seawater over the protective sea wall at the coast. Through containment breaches and fires, these fission products were dispersed over hundreds of kilometers. As noted above, more than 100,000 people were evacuated and relocated to escape from exposure to radioactive fission fragments. The social disruption and psychological distress has been enormous.

A meltdown had occurred earlier, in 1979, at the Three Mile Island nuclear power plant in Pennsylvania, U.S. Although the reactor was destroyed, very little of the radioactivity released within the facility left the reactor site.

A "criticality accident" can also disperse radioactivity from a fission plant. A criticality accident occurred at Ukraine's Chernobyl plant in 1986. The chain reaction at a nuclear reactor is controlled so that fission events occur at a steady rate, but operators at Chernobyl managed to put the reactor into a "runaway" condition where this control was lost. A brief nuclear explosion ensued that breached the reactor containment, resulting in widespread contamination of food, soils, and buildings by the radioactive fission products that had been in the reactor core. Contamination forced the abandonment of large amounts of land and infrastructure and the displacement of even more people than at Fukushima.

At fusion reactors, runaway chain reactions cannot happen. When a fusion power plant experiences a malfunction, the conditions in the reaction chamber change, and fusion inevitably stops. The energy present in a fusion reactor is sufficient to melt individual internal components, but not to breach the containment vessel – where, in any case, far less radioactivity is present than in a fission reactor's core. However, accidents that release radioactivity are still possible. For example, a dramatic failure of a superconducting magnet could cause the vacuum vessel to rupture. This could release tritium and radioactive dust from the vacuum vessel walls, potentially dispersing radioactivity beyond the walls of the facility. Given appropriate plant design, such accidents might not require evacuation of the surrounding area. In one "worst-case" simulation, the "most exposed individual" at a distance of one kilometer from a fusion plant received a dose of radiation less than that experienced during a mammogram *[15,16,17]*. Only in the event of an unprecedented earthquake or similarly energetic event could all safety measures be breached and result in the mobilization of enough radioactive material to require evacuation of the surrounding population *[18]*.

Terrorism and war

The fission power industry is a potential target of attacks by terrorist organizations or military forces. In addition to the loss of electricity production capacity and the proliferation concerns discussed above, the fear is that an attack on a reactor or waste storage site could lead to widespread radiation poisoning. The most commonly feared possibilities are inducement of a meltdown or the deliberate dispersal of radioactive material.

For bad actors to induce a meltdown intentionally at a fission reactor, they would need to disable numerous redundant safety systems. Spent fuel storage buildings, by contrast, are today much less well-protected and therefore more vulnerable to the deliberate disabling of their primary and backup cooling systems *[19,20]*. Fortunately, the radioactivity at spent fuel storage facilities produces heat far more slowly than in reactor cores right after shutdown. As a result, deliberately creating a leak to drain the pool of water in which the high-level waste is stored is less certain to induce a meltdown.

However, a highly energetic external event could mobilize dangerous levels of radioactivity. Detailed studies have not been performed, but it is possible that a bomb or airplane crash could qualify. The amount of radioactivity that could be dispersed is vastly larger for fission plants than fusion plants. In particular, used nuclear fuel from many years of operation of a nuclear fission power plant, full of radioactive fission fragments, is often retained at a fission reactor site, either relatively immobile in dry casks or easily dispersed from pools of water.

Creating and detonating a "dirty bomb" – conventional explosives wrapped in radioactive material – might be less difficult than inducing a meltdown. Attackers could steal or be provided with radioactive material from either fission plants or spent-fuel processing facilities *[20]*. Or they could steal similar material from research reactors, medical therapy machines, food irradiators, and other devices where large amounts of radioactivity are found *[20]*. The U.S. National Research Council (2002) considered the eventual use of a dirty bomb or other radioactivity-dispersing device to be highly probable, with "materials and means... readily available" and "few preventative measures in place" *[19]*.

The tritium and activated materials on the reactor walls at a fusion power plant could be used in a dirty bomb. One study found that the accidental release of 150 grams of tritium or 6 kilograms of tungsten dust from one conceptual reactor would require evacuation of the facility and surrounding areas *[21]*. It follows that such quantities incorporated into a dirty bomb could cause significant contamination. However, it seems unlikely that tritium would be used in a dirty bomb, given that it currently costs about $30,000 per gram; a less expensive, more easily attainable radionuclide would probably be preferred.

The impacts on human health resulting from radiation released by an induced reactor accident or dirty bomb would probably develop slowly. Few people would die from acute radiation poisoning, and the exposure of the surrounding population to a radioactive plume might result in only a small increase in cancer occurrence *[20]*. However, in the event of such an incident, this information might still create panic and lead to serious economic consequences *[19,20]*. The radioactive contamination from an induced meltdown could force the abandonment of large amounts of land and infrastructure, displacing populations for years and creating a level of social distress comparable to what happened at Fukushima. Conceivably, by contrast, a dirty bomb might result in less dislocation and distress, if the bomb contaminated only a few square kilometers and the dispersed radioactivity was promptly cleaned up *[19,22]*.

Overall, the fusion power system presents far smaller risks than the fission power system from the point of view of becoming associated with the malevolent dispersal of radioactivity. Neither the risk of an attack on fusion power infrastructure nor the risk of using fusion waste in a dirty bomb would seem to be significant, though the risk is present. By contrast, despite the numerous safety measures in place, the comparable risks from the fission power system are far higher, both because of the possibility of meltdown and because of the much greater quantities of highly radioactive materials involved.

Table 5.1 summarizes this article through six comparisons of fission and fusion energy systems.

	Fission	Fusion
Primary reaction	Uranium fission	Deuterium-tritium fusion
Radioactive materials of concern: Short-lived	^{131}I, ^{137}Cs, ^{90}Sr	Tritium
Radioactive materials of concern: Long-lived	Activation products, transuranics	Activation products
Risk: Proliferation	Inherent in fuel cycle	Not inherent, but requires safeguards
Risk: Meltdown	Possible	Impossible
Risk: Terrorist attack	Focus of current concern	Minimal

Table 5.1: Summary of the fission-fusion comparisons in this article.

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Article 6: Politics and Progress

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

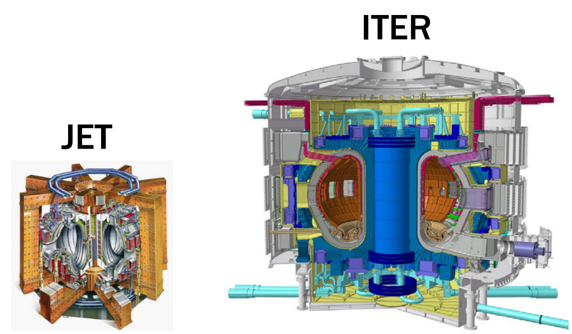
History of global cooperation

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

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

ITER, Latin: "the way"

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



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

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

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

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

Sustaining political investment in ITER

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

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

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

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

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

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

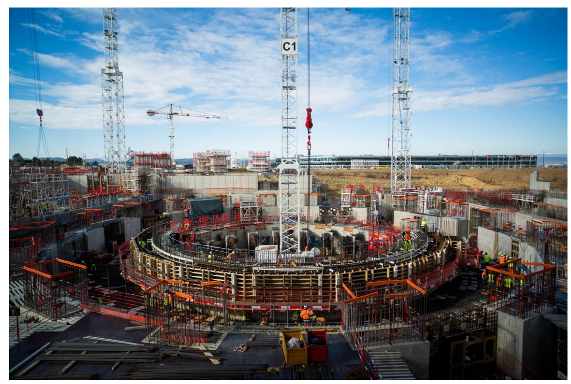


Figure 6.2: After years of delay and continued uncertainty in cost and timeline, ITER construction has begun. The circular structure is the beginning of the building that will house the tokamak. The photo is from February 2016 *[16]*.

Balancing domestic and international priorities

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

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

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

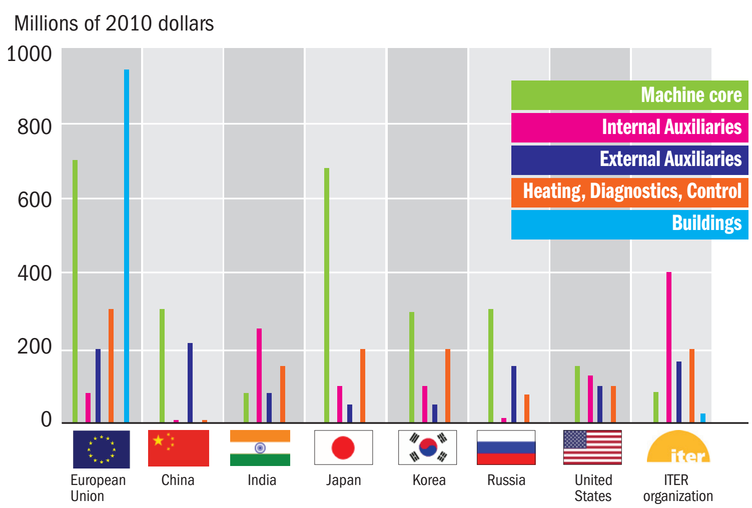


Figure 6.3: Value of the components and sub-systems contributed to ITER by its seven members and by the ITER Organization *[19]*. Ninety percent of each member's contribution is “in-kind” equipment (rather than direct payments) as part of over one hundred discrete procurement packages. The other ten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

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

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

Key domestic research programs

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

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

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

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

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

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

Post-ITER demonstration reactors

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

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

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