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).

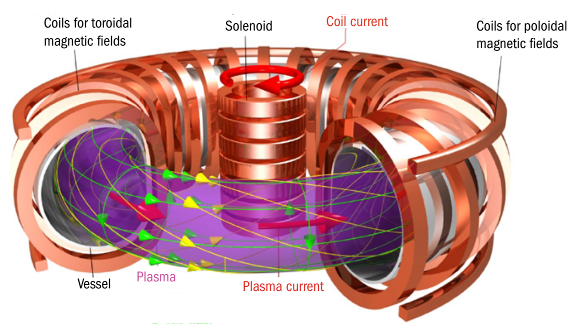

Figure 3.1: Magnetic coils and fields in a tokamak reactor. Note that the coils for the toroidal magnetic fields follow a poloidal path and the coils for the poloidal magnetic fields follow a toroidal path. *Image credit:* Max Planck Institute for Plasma Physics.

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.

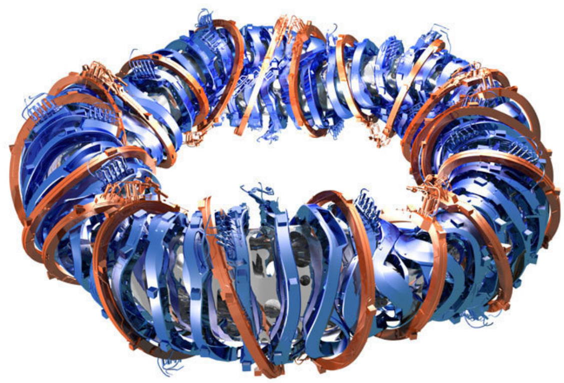

Figure 3.2: Configuration of magnetic coils in the Wendelstein 7-X stellarator *[2]*.

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.

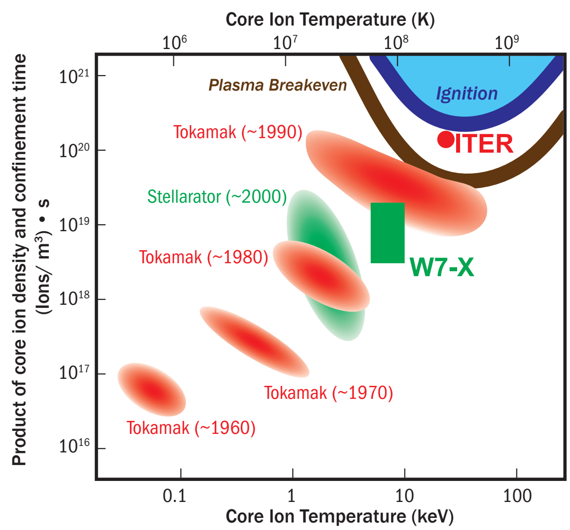

Figure 3.3: Performance of the world's tokamaks and stellarators over the past decades *[3]*. Many devices are included within each oval. The current goals of ITER (a tokamak) and Wendelstein 7-X (W7-X, a stellarator) are also shown. The lower U-shaped band (dark brown) is the approximate region for "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 1×10^{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 2.5×10^{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.

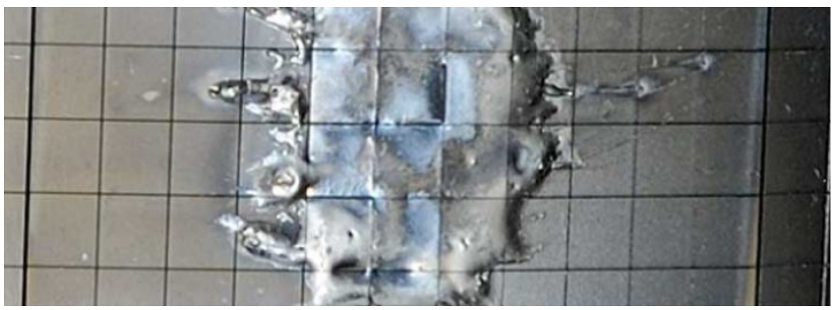

Figure 3.4: A plasma disruption leads to "runaway electrons" striking and partially melting one of the beryllium tiles on a beam protecting the inner wall of the confinement chamber at the JET research facility *[5]*. The thin cut lines on the tile are approximately 12 millimeters apart, and the tile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

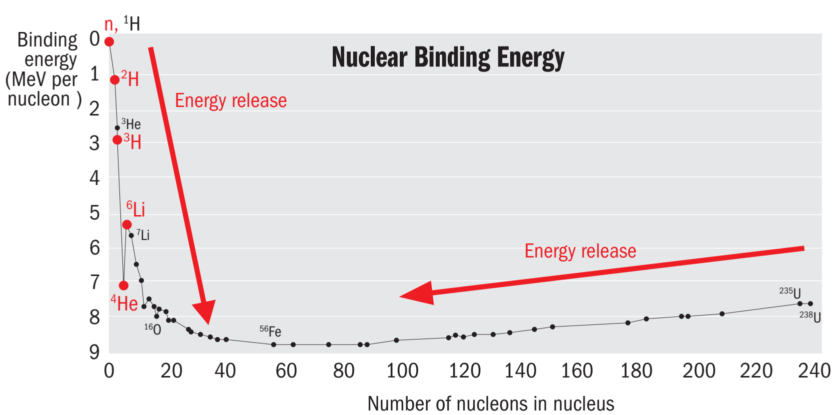

Figure 3.5: "The Curve of Binding Energy" *[6]*: The horizontal axis orders the nuclei in nature by their total number of nucleons (protons and neutrons). The vertical axis is the binding energy per nucleon: the amount of energy required to take apart a nucleus and create separated protons and neutrons, 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.

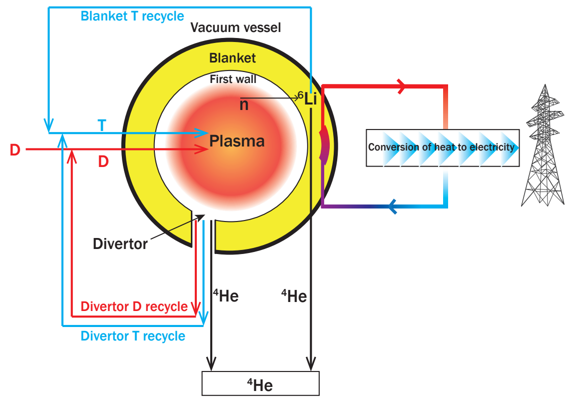

Figure 3.6: Schematic of the materials flows of deuterium, tritium, and helium through a fusion reactor system. *Source:* authors.

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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