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Fusion Energy
via Magnetic Confinement

Energy Technology
Distillate No. 3

This document provides an executive summary of the third Energy Technology Distillate from Princeton University's Andlinger Center for Energy and the Environment. Designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens, this series of briefings covers emerging topics in energy and the environment that combine technological, economic, and policy considerations.

See the full report at http://acee.princeton.edu/distillates. It includes our tutorial: "Key Concepts and Vocabulary."

+Introduction

Nuclear fusion has enormous promise as a global energy source. The fuel is nearly inexhaustible and the waste products have less environmental impact than the wastes associated with fossil fuels and nuclear fission. Making affordable fusion energy would be a remarkable human achievement. To appreciate some of the key challenges, we examine magnetic confinement fusion energy from four perspectives: Technology, Politics and Progress, Economics, and Fusion vs. Fission.

+Technology

Fusion energy is released in certain nuclear reactions where nuclei of atoms combine and are transformed into other nuclei. Since all nuclei are positively charged, they repel each other. But when these nuclei are at a high temperature, they move quickly, and some can get close enough to react. Creating energy from magnetic confinement fusion on Earth requires a temperature of about 200 million degrees Celsius, even higher than the temperature of nature's fusion reactor, the Sun's core, which is 15 million degrees Celsius. At such temperatures, atoms have been stripped of their electrons, and the electrons co-exist with the bare, positively charged ions. This state of matter is called the "plasma" state. In a fusion reactor, very strong magnets are used to confine plasma within a vacuum vessel – with the goals of high plasma temperature, minimal thermal losses, high ion density, and a prolonged period of energy production.

From the 1950s to the 1990s, fusion research focused mostly on magnetic confinement and behavior at the core of the plasma. Over time, attention shifted to the edges of the plasma where heat is lost and materials are damaged – and to the actual production of fusion energy. In the first era, fusion events were minimized because they create radioactivity in the walls of the device and complicate operations. The current step 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.

To attain a burning plasma as a stepping stone to commercial fusion power, the International Thermonuclear Experimental Reactor (ITER) is currently being built in France. ITER should produce 500 megawatts of fusion power for 400 seconds with only 50 megawatts of input power. ITER will also address many engineering issues

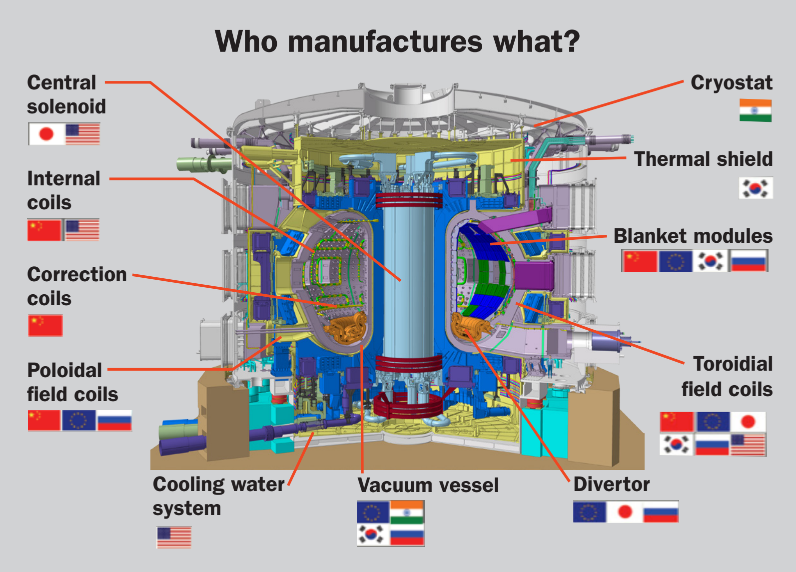

Figure 1: Schematic of the ITER reactor, with flags identifying the members responsible for each component; the members are the European Union, China, India, Japan, Russia, South Korea, and the United States. Source: [1].

such as plasma heating, magnet performance, and the suitability of structural materials.

Plasmas, whose constituents are deuterium and tritium (the heavy isotopes of hydrogen), are by far the most likely to produce a burning plasma. In deuterium-tritium plasmas, the fusion reaction consumes deuterium and tritium and produces a helium nucleus and a neutron. The positively charged helium nuclei slow down within the plasma and keep the plasma hot. However, they must be removed quickly so as not to dilute the plasma and reduce the frequency of deuterium-tritium collisions, which would cool the plasma. The fusion reactor includes a “divertor” to pump helium out of the reactor as fast as it is generated. Making a robust divertor is one of the main challenges of practical fusion.

The electrically-neutral neutrons escape from the plasma and slow down only when they reach the “blanket” surrounding the fusion core. There they create new tritium from lithium in the blanket to compensate for the tritium consumed, and they also produce heat from the neutron-lithium reaction. The tritium must be extracted from the blanket, recycled, and re-injected into the plasma – making blanket design another formidable challenge.

Imagine a large deuterium-tritium power reactor and its associated blanket producing electricity at a rate of 1,000 megawatts (roughly the size of nuclear fission plants and coal plants today), running 90 percent of the time, and converting into electricity 40 percent of the fusion energy produced in the plasma and blanket. Approximately 80 kilograms of deuterium and 120 kilograms of tritium would be consumed each year. A future global energy system with a central role for fusion, say a world with 1,000 one-thousand-megawatt plants, would consume 80,000 kilograms of deuterium per year. In the absence of tritium regeneration from lithium in the blanket, it would also consume 120,000 kilograms of tritium per year.

The job of isolating sufficient deuterium for fusion reactors is not difficult. Even though only one out of every 6,500 hydrogen atoms on Earth is deuterium (the rest are ordinary hydrogen), the world’s largest deuterium-production facility was able to separate 140,000 kilograms of deuterium per year. Thus, a single such plant could produce sufficient deuterium for more than a thousand large (one-thousand-megawatt) fusion plants.

By contrast, tritium is radioactive and essentially is not found on Earth, so that tritium management is a major task for fusion. A mature fusion industry will require that more tritium is generated in the blankets than is consumed in the plasmas. But it is unclear how the tritium needed for the first fusion power plants will be produced. The current stockpile of tritium from nuclear power plants may not be sufficient to launch the industry, in which case producing tritium for early fusion plants may become a new task for the world’s nuclear fission reactors over the coming decades.

In parallel with magnetic confinement fusion, inertial confinement fusion is being investigated, which seeks to drive fusion reactions by compressing matter to very high densities with laser beams that converge on small pellets. The same fusion reactions are involved in both cases, but the obstacles in the path to commercialization of fusion energy are entirely different.

+ Politics and Progress

The quest for fusion power has generated one of the world’s most ambitious international collaborations in science and technology. Nations struggle to align expensive experiments with bounded budgets and to balance the funding of domestic and multinational programs.

The ITER project is expected to begin operating in 2026 at a cost of more than $20 billion. Figure 1 shows the ITER device with flags that identify which of its seven members is building each of its major components. The European Union, the host, is contributing approximately 45 percent of the costs; China, India, Japan, Russia, South Korea, and the United States are sharing the other 55 percent equally.

It is still possible that ITER will not be finished if its members lose patience with repeated delays and rising costs. It is also possible that ITER’s technical goals will not be realized, because the burning plasma reveals intrinsic complications. Assuming that ITER’s technical goals will be realized, 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. 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.

Simultaneous with the planning in the framework of DEMO, several nations are already planning single-nation post-ITER experiments. Although in both the past and current era international collaboration has been the norm for fusion, if at some point commercial viability emerges, collaboration among nations may fade in favor of competition for market share.

+ Economics

The cost of fusion power

Estimates of the cost of a fusion power plant vary widely, which is hardly surprising since many important determinants of the cost are not known. The costs come in two categories: the cost of the initial capital and the costs to keep the plant running.

Figure 2 is representative of published cost estimates. Of the total cost of electricity, 73 percent is associated with building the plant, about the same as the percent for coal and nuclear fission plants. But some of the remaining costs are uniquely important for fusion. The two striped components in Figure 2, totaling 16 percent of the costs, are for periodic replacement of important structural components whose performance has been compromised as a result of neutron bombardment. The “divertor” and the “first wall” of the blanket are particularly vulnerable because they face the plasma. Neutron bombardment weakens a structural material not only by displacing atoms from their sites but also by producing helium via nuclear reactions at these sites, resulting in swelling. Looming over fusion is the concern that component replacements will not be straightforward and will require costly plant shutdown for months at a time.

A second threat to nearly continuous operation of a fusion power plant comes from the possibility that severe plasma instabilities will drive the hot plasma into a wall and lead the reactor to shut itself down automatically to avoid significant damage. Fusion research – since its inception – has sought to control plasma instabilities; the additional instabilities expected from a burning plasma could make the control of a fusion reactor even more daunting.

Fusion’s market share in the 21st century

The extent to which fusion could contribute to global electricity production in this century is highly uncertain. Not only is the cost trajectory for fusion unknown, but so are the cost trajectories for fusion’s competitors. For example, the future cost of nuclear fission power depends on whether substantial extra costs will be incurred that reflect broad public mistrust of the technology. Fusion’s future also depends on the evolution of climate policy. Fusion is a low-carbon energy source, and strong climate policy (for example, a high tax on carbon dioxide emissions into the atmosphere) will disadvantage coal, oil, and gas, relative to fusion and other non-fossil energy sources. However, a strong carbon policy may also lead to low-carbon versions of fossil-fuel power plants, called carbon dioxide capture and storage (CCS) power plants, where much of the carbon dioxide produced at the plant ends up deep below ground in geological formations rather than in the atmosphere.

A representative market-share study of the 21st-century global energy system assumed that fission and fusion by mid-century will have nearly the same cost and determined that:

- Without a target for reduction of carbon dioxide emissions, fusion’s share of electricity at the end of the century is small.
- Strengthening either the carbon target or the constraints placed on fission and CCS increases fusion’s market share.

Two extreme cases are shown in Figure 3. In Panel I, where there is neither climate policy nor special constraints on fission and CCS, fusion’s share of global electricity in 2095 is just four percent. In Panel II, the world maintains a tough climate policy, fission is more expensive than in Panel I, and CCS deployment is limited by geological storage space. In that case, fusion’s market share is 32 percent. Additionally, total electricity production is higher in Panel II because electricity is favored over the direct use of fuels when there is a carbon tax – think, for example, of electric cars.

Even for Panel I, fusion produces substantial electricity at the end of the century: four trillion kilowatt-hours each year – approximately the scale of the deployment of nuclear fission power today. Respectively, in Panels I and II, about 500 versus 5,000 one-thousand-megawatt fusion plants are on-line in 2095.

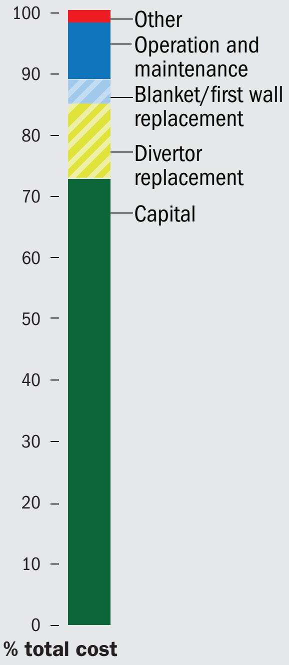

Figure 2: Components of the total cost of electricity produced by a magnetic confinement fusion reactor, shown as a percent of total cost. The two components shown with stripes are costs for replacement of critical elements of the reactor whose lifetime, due to neutron bombardment, could be much shorter than the rest of the reactor. Source: [2].

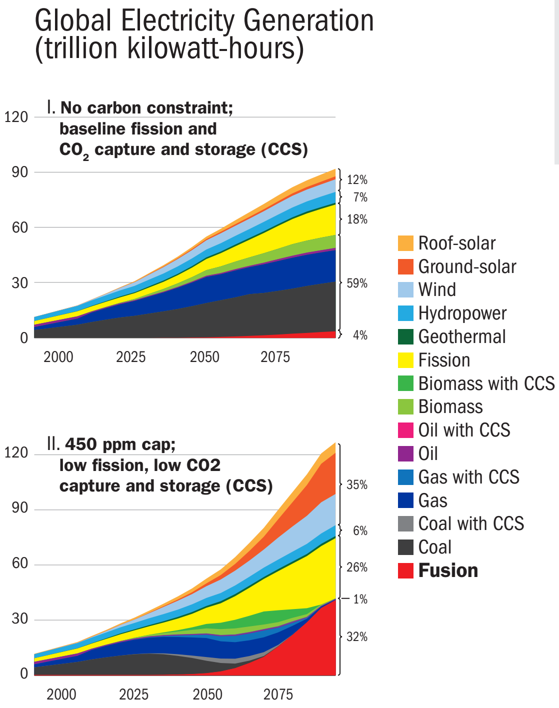

Figure 3: Production of global electricity in the 21st century when fusion is an option, by energy source. Above: Unfavorable to fusion: no carbon policy; fission and carbon dioxide capture and storage (CCS) are fully available. Below: Favorable to fusion: a 450 parts per million climate target; fission and CCS are constrained. Source: [3].

+ Fusion vs. Fission

The risks from fusion and fission power can be compared in at least these four ways: nuclear weapons proliferation, radioactive waste, reactor accidents, and terrorist or military attack. In general, the risks from fusion power are smaller. But will quantitative differences be seen as qualitative differences? Will fusion receive a warmer welcome than fission?

Nuclear Weapons Proliferation

Civilian fission power is tightly linked to fission weapons through two special materials: plutonium and highly enriched uranium. The uranium found in nature cannot be used for weapons without the challenging modification called isotope enrichment. Uranium fuel for most nuclear power plants is somewhat enriched, and “weapons-grade” uranium is further enriched using the same technology. Plutonium is a by-product of the reactions in fission power plants, but it is unavailable for weapons unless it is deliberately separated from the highly radioactive “spent fuel” in which it resides. Thus, fission power represents a step toward the materials for an atomic bomb, but the next steps are not inevitable.

Fusion reactions do not use or produce fissionable material. If thorium or uranium were illicitly brought to a fusion plant for neutron bombardment, weapons-related material could be produced, but it would be difficult to disguise this activity since there is no good reason to have either thorium or uranium at the site in the first place.

Waste disposal

A nuclear fission event inevitably creates radioactive fission fragments. In addition, in a reactor, the neutrons produced in the same fission event create radioactivity as they are absorbed by both the fuel itself and structural materials. The fission fragments, the altered fuel, and the irradiated materials all have a wide range of half-lives – from less than a second to millions of years. Radioactive materials with very long half-lives require, by law, management for thousands of years.

In a deuterium-tritium fusion plant, there is no equivalent of fission fragments or transformed fuel, but tritium itself is radioactive and, as with fission, neutron bombardment produces radioactive structural material. Tritium is a central concern because, being a radioactive heavy isotope of hydrogen, it acts chemically like ordinary hydrogen and is readily incorporated into water and live biological tissue. As for structural materials, current research seeks “low activation” variants of standard materials, such as steel, that will simplify storage requirements.

Reactor accidents

A fission reactor can experience a meltdown if its cooling system fails, and it can experience a runaway chain reaction if its controls fail. A meltdown followed by hydrogen explosions occurred at several of the reactors at Fukushima Daiichi in Japan after an earthquake and tsunami in March 2011. A runaway reaction occurred at Ukraine’s Chernobyl plant in 1986 when its controls were improperly used. In both cases, radioactivity was widely dispersed, leading to extensive contamination of food, soils, buildings, and the displacement of entire communities.

At fusion reactors, a runaway chain reaction cannot happen because a malfunction leads fusion to stop. However, accidents that could release tritium and radioactive structural material beyond the walls of the facility are still possible.

Terrorism and war

Fission power plants and their fuel-cycle facilities are potential targets of attacks by terrorist organizations or military forces, and fusion facilities may someday be thought of in the same way. Only fission reactors are at risk of a deliberately induced meltdown, but attacks on either fission and fusion sites could lead to the dispersal of radioactive material.

A second concern is the malevolent dispersal of radioactive material in a “dirty bomb.” Not only the fission power system, but also medical therapy machines and food irradiators are potential sources. Conceivably, the tritium inventory of a fusion facility could be raided for the same objective of societal disruption.

References

[1] Courtesy of Bernard Bigot (director of ITER). Presentation at the 2015 Annual Meeting of the Fusion Power Associates, 16 December 2015.

[2] Maisonnier, D., Cook, I., Sardain, P., Andreani, R., Di Pace, L., Forrest, R., Giancarli, L., Hermsmeyer, S., Norajitra, P., Taylor, N., et al. (2005). A conceptual study of commercial fusion power plants: Final report of the European Fusion Power Plant Conceptual Study (PPCS). European Fusion Development Agreement.

[3] Turnbull, D. (2013). Identifying new saturation mechanisms hindering the development of plasma-based laser amplifiers utilizing stimulated Raman backscattering. Ph.D. Dissertation. Princeton University, USA.

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