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Fusion Energy

The federal government has supported fusion energy research and development (R&D) for decades. In recent years, congressional interest in fusion has grown in response to scientific progress by fusion researchers, the emergence of a growing commercial fusion industry, and hope that future fusion power plants can contribute to the nation's electricity needs without emitting carbon dioxide—a greenhouse gas that contributes to climate change.

What Is Fusion?

Fusion is a nuclear process in which the nuclei of two light atoms (such as hydrogen) join, or fuse, to form a heavier nucleus, releasing energy. Fusion is, in that sense, the opposite of fission—the nuclear process that powers today's nuclear power plants—in which the nucleus of a heavy atom (such as uranium) splits into two lighter nuclei. Fusion of hydrogen into helium is the power source that makes the Sun shine. On Earth, explosive fusion powers nuclear weapons, but controlled fusion for electricity production is yet to be demonstrated.

Why Fusion Energy?

A fusion power plant would have a number of advantages over today's fission-based nuclear reactors. First, it would not require nuclear fuel such as uranium or plutonium. The use of these fuels in fission reactors has raised concerns about nuclear weapon proliferation, since their availability may facilitate weapon development. In addition, the United States has fraught relationships with some countries that are major uranium sources, such as Russia. In contrast, the most common fusion reactor designs are fueled by a mixture of two hydrogen isotopes: deuterium and tritium. Deuterium is abundant and available domestically. Tritium can be manufactured from lithium, potentially in fusion reactors themselves, and is sourced mostly from Canada.

Safety is also a potential advantage for fusion when compared with fission. Fusion reactors do not pose a meltdown risk—the challenge for fusion is keeping the reaction going, not keeping it under control or removing residual heat as with fission. Unlike fission, fusion creates little radioactive waste, although structural materials in the reactor may become somewhat radioactive over time through a process known as neutron activation.

The operation of a fusion reactor would not directly emit carbon dioxide, unlike power plants based on the combustion of fossil fuels. The manufacturing of reactor components and the construction of the reactor itself would likely result in some carbon dioxide emissions; that is true of any large facility, including facilities for electricity production from renewable sources such as wind and solar.

Developing fusion energy remains technically challenging. No grid-connected fusion reactors currently exist. Current systems are all designed for R&D, and none of them include systems to convert the released energy into electricity. Fusion ignition (defined as a fusion reaction that releases more energy than the amount consumed to initiate and maintain the reaction) has not yet been achieved in the most commonly proposed power plant configuration. Extensive R&D remains necessary on aspects such as the materials and magnets needed for reactor construction, the development and testing of competing reactor designs, and the integration of reactor designs with systems for converting heat to electricity.

Plasma Confinement

A key challenge for maintaining a controlled fusion reaction is confining the fuel. Fusion reactions take place in hot, dense, ionized gas called plasma. The plasma fuel for the reaction must be confined to keep it hot and dense so the reaction can continue. The Sun's plasma is confined by the pull of the Sun's own gravity. For fusion power plants on a human scale, two other strategies have been developed: magnetic confinement and inertial confinement.

In magnetic confinement, the plasma is held in place using magnetic fields. This is the most common choice both for current research reactors and for planned power plant designs. A widely used configuration known as a tokamak uses powerful magnets to confine the plasma within a toroidal (donut-shaped) reaction vessel, with the magnetic fields keeping the plasma away from the walls of the vessel to prevent damage and unintended cooling of the plasma.

In inertial confinement, powerful lasers create rapid fusion reactions in short bursts, with each reaction completing before the plasma fuel has time to disperse. This approach is used, for example, in the National Ignition Facility (NIF) at the Department of Energy (DOE) Lawrence Livermore National Laboratory. While the NIF is intended primarily for research to improve stewardship of the U.S. nuclear weapons stockpile, its demonstration of fusion ignition in December 2022 has increased interest in inertial confinement designs for future power plants.

Federal Fusion R&D

Most federally funded fusion energy R&D is supported by the DOE Office of Science through its Fusion Energy Sciences program. The program has a budget of $763 million in FY2023, which the Administration has proposed to increase to $1.010 billion in FY2024. The main emphasis has been on magnetic confinement, though in recent years the program has expanded its efforts on inertial confinement. The program has also historically focused mostly on basic research, though in recent years it has pivoted toward a greater emphasis on applied research. The ITER facility (see below) is a priority for the program, accounting for $242 million of its budget in FY2023.

The DOE Advanced Research Projects Agency–Energy (ARPA-E) also supports some fusion energy projects, along with other projects across the full range of energy technologies. In general, ARPA-E focuses more on applied research and commercialization than the Office of Science does. It also generally requires cost-sharing, which the Office of Science generally does not. Current ARPA-E programs with a fusion focus include Breakthroughs Enabling Thermonuclear-Fusion Energy (BETHE, total funding $35 million) and Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts (GAMOW, total funding $29 million). In November 2022, ARPA-E issued a request for information on potential future R&D programs on enabling technologies for improving fusion power plant performance and availability.

In the DOE National Nuclear Security Administration, the Inertial Confinement Fusion program is focused on the use of fusion science to improve stewardship of the U.S. nuclear weapons stockpile. Its FY2023 budget is $630 million. The program includes the NIF, mentioned above, among other activities. Although the program's emphasis is on nuclear weapons applications, some of its scientific advances may also be applicable to fusion energy, especially to reactor designs based on inertial confinement.

ITER

ITER (formerly an acronym for International Thermonuclear Experimental Reactor) is a fusion energy research and demonstration facility currently under construction in France. ITER is an international collaboration involving the United States, China, the European intergovernmental organization Euratom, India, Japan, South Korea, and Russia. Demonstrating "burning plasma" (operation at or near ignition) in a magnetic confinement design is the facility's key goal. Its planned capabilities also include extensive instrumentation for advancing the scientific understanding of fusion plasmas, as well as opportunities for testing specialized materials for use in fusion applications.

The ITER project has a history of budget and schedule challenges. The total U.S. share of the project's cost is currently estimated at $6.5 billion, mostly through in-kind contribution of reactor-component design and fabrication. This represents about 10% of the total international cost. The project expects to create its first plasma in 2028, with full operations due to start in 2035 and an expected useful life of 35 years. DOE plans to confirm a revised cost and schedule baseline during 2023. The potential impact of ITER's funding needs on resource availability for domestic U.S.-based fusion R&D has sometimes been a concern in both Congress and the scientific community, especially in times of a tight fiscal environment.

Commercial Fusion Industry

A new development in recent years is the emergence of a commercial fusion industry, involving several dozen companies and announced private investment approaching $5 billion. These companies are pursuing a wide variety of designs, using a variety of fuels. Magnetic confinement of deuterium-tritium fuel is the most common approach, as in the federal R&D effort, but the approaches taken by the commercial sector are more diverse than current federal programs, and more often use design strategies traditionally seen as alternative. Most companies are targeting delivery of electricity to the grid by the mid-2030s. Some observers consider that an ambitious goal.

Recent Legislation, Regulatory Action, and Policy Studies

Congress has taken several legislative actions regarding fusion energy in recent years. Section 2 of the Nuclear Energy Innovation Capabilities Act of 2017 (P.L. 115-115), Section 3 of the Nuclear Energy Innovation and Modernization Act (P.L. 115-439), and Section 2002 of the Energy Act of 2020 (P.L. 116-260, Division Z) all defined the term *advanced nuclear reactor* (in different contexts) to include fusion reactors, making fusion R&D potentially eligible for various DOE nuclear energy programs previously focused exclusively on fission. Section 2008 of the Energy Act of 2020 mandated a policy pivot in the Fusion Energy Sciences program from basic research toward commercialization and public-private partnerships. Section 10105 of the CHIPS and Science Act (P.L. 117-167) reauthorized the Fusion Energy Sciences program, including a mandate for the establishment of national teams to design a pilot plant "that will bring fusion to commercial viability." Section 50172(a)(3) of the Inflation Reduction Act of 2022 (P.L. 117-169) provided supplemental appropriations to the Fusion Energy Sciences program for construction and equipment, largely related to ITER.

In 2021, the Nuclear Regulatory Commission (NRC) began to consider options for a regulatory framework for fusion power plants. In early 2023, NRC staff submitted a report to the Commissioners evaluating three options: (1) regulating fusion energy systems as "utilization facilities," similar to the framework currently used for fission-based reactors; (2) regulating them under the "byproduct material" framework (10 C.F.R. Part 30), which would address any radioactive material present in a fusion facility but not the detailed operation of the facility; and (3) a hybrid approach combining the first two options, with the utilization facilities component deferred unless detailed designs emerge with greater risk profiles or other concerns than currently contemplated facilities. The staff report recommended the hybrid option, but in April 2023, the Commission voted to adopt the byproduct material option, which the commercial fusion industry generally considers the least burdensome.

Recent policy studies include a long-range plan issued in 2020 by DOE's Fusion Energy Sciences Advisory Committee, titled *Powering the Future: Fusion and Plasmas*; a 2021 study by the National Academies of Sciences, Engineering, and Medicine, titled *Bringing Fusion to the U.S. Grid*; a White House summit in 2022 on *Developing a Bold Decadal Vision for Commercial Fusion Energy*; and a 2023 technology assessment by the Government Accountability Office, titled *Fusion Energy:*

Potentially Transformative Technology Still Faces Fundamental Challenges.

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