EPRI | ELECTRIC POWER RESEARCH INSTITUTE

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

Harnessing Fusion Energy

INTRODUCTION

Commercial nuclear power plants produce electricity from heat generated by the splitting of heavy elements—a process known as fission. This is not the only way of releasing nuclear energy. The sun and other stars are powered by fusion—the opposite of fission—in which energy is released when the nuclei of lighter elements such as hydrogen and helium combine to form heavier elements and release energy in the process.

Harnessing fusion's potential is no easy feat. Positively charged nuclei naturally repel each other. This electromagnetic force must be overcome by providing the conditions to force lighter nuclei together. Once close enough, the attractive strong nuclear force takes over, fusing the nuclei together into a single heavier nucleus. If the mass of the new nucleus is less than the sum of its parts, the mass difference is converted into large amounts of energy in keeping with Einstein's well-known equation, $E = \Delta mc^2$. Figure 1 depicts the fusion of deuterium (^2H) and tritium (^3H) nuclei, two isotopes of hydrogen, to yield helium and energy in the form of fast-moving particles and heat.

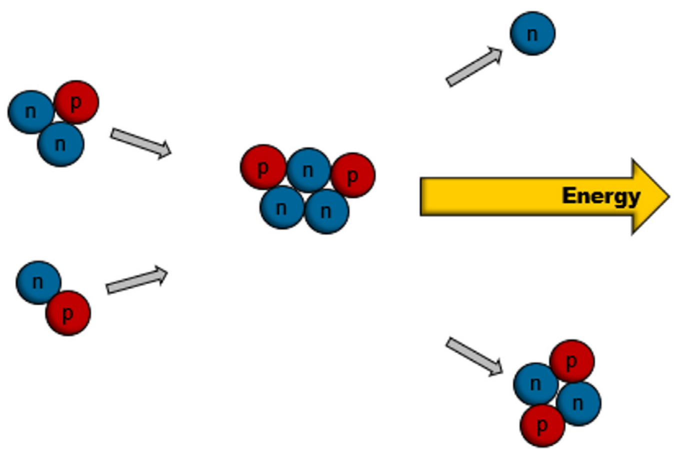

Figure 1. Illustration of D-T fusion, in which deuterium and tritium nuclei combine to form a stable helium nucleus and release a neutron and energy.

While fusion energy has been proposed as a sustainable answer to global energy needs, exploiting fusion for practical power generation has yet to be demonstrated. Breakeven is the condition in which a fusion facility produces as much energy as was used to initiate or maintain the reaction. For fusion to offer a viable commercial option, a fusion generator would need to produce more energy than consumed, i.e., $Q_E > 1$. To date, engineering breakeven ($Q_E = 1.0$) remains to be achieved. The fusion community has adopted a nearer-term goal of plasma break-even, or $Q_P>1$, in which the energy used to heat a fusion plasma is less than the energy it produces through fusion. The higher the Q_P achieved, the less risk involved in reach $Q_E>1$.

Key Terms

Nucleus: The positively charged center of an atom, comprising positively-charged protons and charge-free neutrons. (plural: Nuclei)

Fusion: Process by which smaller, lighter nuclei combine to form a larger, heavier nucleus and release energy; this is the energy source of the sun and other stars.

Plasma: The highly energetic state of matter in which electrons have been stripped from their nuclei, resulting in a 'soup' of charged particles.

Confinement: Approach used to maintain plasma conditions, especially density and temperature, required for fusion to occur.

Ignition: The point at which the fusion chain reaction becomes self-sustaining, or when the energy produced is enough to initiate further fusion reactions under stable confinement conditions.

Q_P: The ratio of fusion energy produced in a nuclear fusion plasma to the energy used to heat the plasma.

Q_E: The ratio of fusion energy produced in a nuclear fusion facility to the energy used to operate the entire facility at steady state.

Aneutronic: Fusion approaches and fuel options in which less than 1% of the energy produced in a fusion reaction is released in the form of neutrons.

FUSION CONFINEMENT

Modern approaches to fusion can be classified by the method by which the requisite conditions for fusion are established and maintained – confinement.

The first approach uses strong magnetic fields to contain the plasma fuel and is referred to as magnetic confinement fusion (MCF). Research on MCF has been ongoing since the late 1940s and has resulted in two primary technologies: the tokamak and the stellarator. Both of these approaches employ a set of magnetic coils to produce twisting magnetic field lines along a donut-shape torus to contain the plasma. Of the two, the tokamak is the more common concept, has achieved the highest performance, and has long been considered the leading fusion design. MCF devices can operate in both continuous and pulsed modes.

Inertial confinement fusion (ICF) offers a second approach to controlled fusion. Instead of relying on powerful magnetic fields, physical compression with clever applications of Newton's Third Law of Motion is used to provide the confinement needed to achieve fusion. The most common approach uses powerful lasers focused on a small fuel-containing target, resulting in the rapid heating and explosion of the outer target layer. This yields an opposing compressive force on the internal fuel sufficient to induce fusion. ICF is necessarily a pulsed fusion process.

A third category, magneto-inertial fusion (MIF), encompasses methods exploiting aspects of both magnetic and inertial confinement.

FUSION FUELS

Multiple fuel options and approaches for fusion are theoretically possible. Of the options, deuterium-tritium (D-T) fusion ignites at the lowest temperatures and has the greatest output energy. There are other factors worth considering when selecting a fuel, such as the amount of energy that is produced and carried away in the form of neutrons that must be captured for use, and can lead to significant damage in those materials in closest proximity to the plasma (IAEA, 2012). While all realistic fuels produce significant neutron fluxes, and give rise to material challenges, the more energetically favorable fuels, such as D-T, produce greater neutron fluxes.

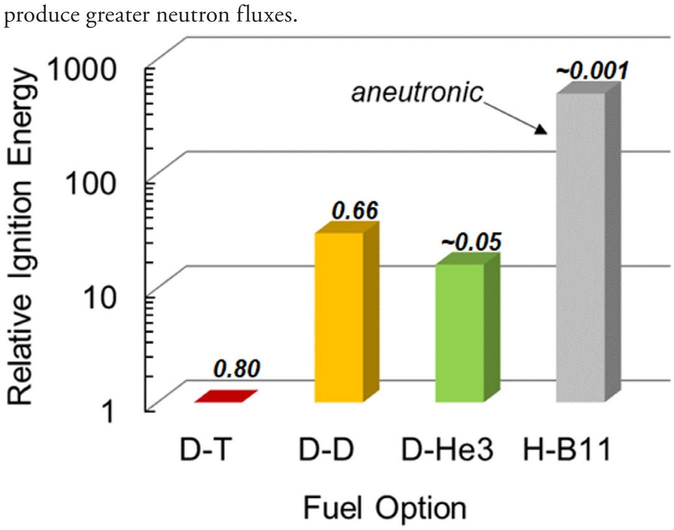

Figure 2. Ranking of fusion fuels by ignition energy.

Leading fusion fuel options are shown in Figure 2, with the required ignition energy normalized to D-T fusion on the vertical axis. Values corresponding to the number of neutrons produced per reaction are shown above the bar (IAEA, 2012).

MAJOR CONVENTIONAL FUSION PROJECTS

Conventional approaches to fusion employing D-T fuel are generally rooted in publicly funded R&D programs at national laboratories and academic institutions. The International Thermonuclear Experimental Reactor (ITER), a joint endeavor of China, the European Union, Japan, Korea, Russia and the United States, represents the state-of-the-art public-sector magnetic fusion experiment on a grand scale. Construction is scheduled to finish in 2025 in Cadarache, France. With costs to first plasma estimated at $22 billion USD (Kramer, 2018), ITER would be the second most expensive scientific project in human history—behind only the International Space Station.

ITER is a D-T-fueled tokamak featuring a plasma volume 10 times greater than its predecessor, the Joint European Torus (JET). At this scale, ITER is designed to finally cross the fusion plasma breakeven milestone, producing more thermal energy than sustaining the plasma consumes. An ITER successor, the even-larger Demonstration Power Plant (DEMO), is already being proposed to build upon ITER experience. If successful, DEMO would represent a prototype for a commercial fusion power plant; however, the projected 2050 timeframe for operation offers a three decade window of opportunity for development and commercialization of competing energy technologies, including novel and nimble commercial fusion entrepreneurs.

ALTERNATIVE FUSION PATHS AND BUSINESS MODELS

Alternatives to the large, conventional systems have been proposed for viable commercial fusion power production on smaller, more economical scales. In design space, many seek to optimally exploit and combine the best of both worlds with respect to magnetic and inertial confinement approaches through hybrid approaches. A second camp is pursuing "cusp confinement" fusion (CCF).

In addition to confinement options, the pursuit of aneutronic fuel cycles, which impose significantly increased confinement requirements (e.g., Figure 2) is viewed by some developers as an acceptable if not strategic tradeoff in return for the benefits of avoiding tritium management issues and a reduction to the material performance and radioactive waste management challenges that accompany high-energy neutron bombardment of materials. General Fusion and TAE Technologies (formerly Tri-Alpha Energy) offer examples of private-sector developers pursuing alternative fusion approaches and aneutronic fuel cycles, respectively.

The nearest-term experiment targeting $Q_P > 1$ is SPARC, a joint effort of Commonwealth Fusion Systems (CFS) and the Massachusetts Institute of Technology (MIT). Due to be commissioned in 2025, SPARC pursues the conventional tokamak design, but made more compact and powerful by the use of high-temperature superconducting magnets.

Table 1. Summary of major government-funded fusion projects.

Facility – Location	Institution or Company	Confinement – Approach
ITER – France	ITER Project, an international consortium	MCF – Tokamak
Joint European Torus (JET) – United Kingdom	Culham Centre for Fusion Energy, Euratom	MCF – Tokamak
SPARC – United States of America	Commonwealth Fusion Systems and the Massachusetts Institute of Technology	MCF – Tokamak
Experimental Advanced Superconducting Tokamak (EAST) – China	Institute of Plasma Physics, Chinese Academy of Sciences	MCF – Tokamak
DIII-D – United States of America	General Atomics, U.S. Department of Energy	MCF – Tokamak
Wendelstein 7-X (W7-X) – Germany	Max Planck Institute for Plasma Physics	MCF – Stellarator
National Ignition Facility (NIF) – United States of America	Lawrence Livermore National Laboratory	ICF – Laser-driven
Laboratory for Laser Energetics – United States of America	University of Rochester	ICF – Laser-driven
Laser Mégajoule – France	French Alternative Energies and Atomic Energy Commission (CEA)	ICF – Laser-driven
Z Pulsed Power Facility (Z Machine) – United States of America	Sandia National Laboratory	ICF – Z-pinch

In General Fusion's magnetized target fusion design, one of several MIF variants, fuel in the form of magnetically confined D-T plasma is injected inside a rotating spherical shell of liquid metal, which is then rapidly compressed mechanically, producing a powerful shock wave resulting in pulsed fusion. Figure 3 depicts the latest plasma fuel injector and the overall scale of design, development, manufacturing, and testing (General Fusion, 2020).

TAE Technologies design invokes the field-reversed configuration (FRC) as an alternative to traditional MCF. TAE's pursuit of aneutronic operation has reached a number of important milestones, including the achievement of plasma temperatures in excess of 50 million °C in the C2W Norman device shown in Figure 4 (TAE Technologies, 2017).

While government-sponsored R&D has been primarily focused on large-scale experiments and conventional approaches, there is growing interest in exploring alternative approaches promising lower costs and smaller scales—many of which are being driven by the private sector.

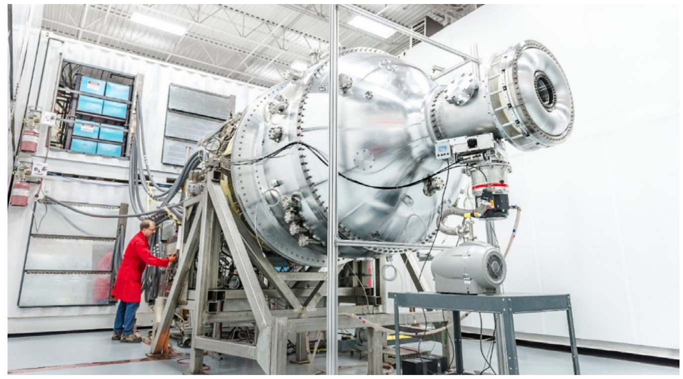

Figure 3. General Fusion's latest generation of plasma injector (© 2018 General Fusion. Used with permission.)

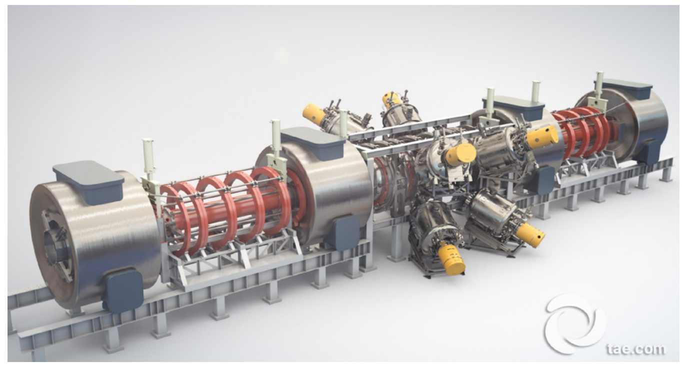

Figure 4. TAE Technologies C2W Norman Fusion Platform (© 2019 TAE Technologies, used with permission)

PRIVATE-SECTOR INTEREST AND INVESTMENT

As private-sector ventures like SpaceX begin to enter fields that have been the exclusive domain of governments historically, private fusion companies are similarly pursuing innovative, market-driven approaches. These have the potential for accelerated pathways to commercialization relative to larger research-oriented national and international projects.

In contrast to the traditional "big-science" approach sponsored by government programs, the private-sector ventures are targeting fusion concepts deployable at smaller scales, which could prove commercially advantageous given current trends in nuclear fission energy toward smaller and more modular plants.

Private investment in fusion has also grown substantially, with an estimated cumulative total of over $1.5 billion USD flowing to more than a dozen companies (Kramer, 2020). In 2018 the fusion industry took another step forward with the launch of an industry trade organization, the Fusion Industry Association. Since then, the U.S. Department of Energy formed INFUSE, a fusion counterpart to GAIN; while ARPA-E continues funding through the ALPHA, BETHE, and GAMOW programs.

While these fusion startups are primarily backed by private capital, many were influenced by and benefitted from publicly-sponsored R&D at universities and national laboratories.

COMMON TECHNOLOGY ISSUES AND COLLABORATIVE OPPORTUNITIES

In spite of the diversity in fusion approaches, there are common challenges faced by the developer community that appear amenable to collaborative research, development, and demonstration activities. These include:

Materials: Most of the energy produced in the D-T reaction is carried in the form of neutrons. Materials and components exposed to high-energy neutron bombardment can suffer embrittlement and structural fatigue that threaten system performance and integrity.

Advanced manufacturing: Incorporation of components with complex geometries and refractory and non-metallic materials will likely introduce challenges for fabrication and qualification. New fabrication, joining, and cladding methods being developed and demonstrated in other fields could be leveraged to improve fabricability and support supply chain development.

Radioactive waste management: While fusion does produce a modest amount of low-level waste, it does not produce any of the high-level radioactive waste that is generated at fission facilities.

Heat exchangers: Efficient heat removal for practical use and cooling requires adequate heat exchanger performance with respect to design constraints, pressures, temperatures, and coolant compatibility.

Table 2. List of privately funded fusion projects

Vendor	Headquarters	Confinement – Approach
TAE Technologies	Foothill Ranch, CA	MCF – Field reversed
Princeton Satellite Systems	Plainsboro, NJ	MCF – Field reversed Direct drive
Commonwealth Fusion Systems	Cambridge, MA	MCF – Tokamak
Tokamak Energy	Oxfordshire, UK	MCF – Spherical Tokamak
CT Fusion	Seattle, WA	MCF – Spheromak
HB11 Energy	New South Wales, Australia	ICF – Laser-driven
Innoven Energy	Colorado Springs, CO	ICF – Laser-driven
Proton Scientific	Urbana, IL	ICF – Electron beam
LPP Fusion	Middlesex, NJ	ICF – Dense plasma focus
First Light Fusion	Yarnton, UK	ICF – Shock wave
HyperJet Fusion	Chantilly, VA	MIF – Magnetized Target
General Fusion	Burnaby, BC	MIF – Magnetized Target
AGNI Energy	Lacey, WA	MIF – Magnetized Target
MIFTI	Irvine, CA	MIF – Staged Z-pinch
Horne Technologies	Louisville, CO	MIF – Inertial electrostatic
Helion Energy	Redmond, WA	MIF – Field reversed
Lockheed Martin	Bethesda, MD	CCF – Magnetic mirror

Fuel supply: Tritium is not naturally abundant and therefore must be produced via an appropriate nuclear process. Many D-T fusion systems propose the inclusion of a lithium-6 based breeding blanket, but these systems are complex and require further development. Other fuels like ^{3}He, while featuring the lowest energy threshold for aneutronic fission, are very rare on Earth's surface (but can be potentially harvested on the moon's surface).

Energy and power conversion: Although conventional power conversion systems are suitable for electricity generation from fusion, more advanced technologies such as supercritical CO_2 Brayton cycles and direct energy conversion technologies represent potential enablers for improved economics, efficiency, and performance.

EPRI Perspective

Growing interest in the potential of fusion power systems, fueled by progress made by private companies pursuing non-conventional approaches, has prompted renewed scouting efforts led by the Advanced Nuclear Technology program.

In 1994, EPRI convened a panel (of utility leaders) to identify criteria for practical fusion power systems. The panel identified three key focus areas:

- Economics—fusion power systems must be competitive with alternatives in terms of lifecycle costs and commercial performance.
- Public acceptance—the environmental and safety potential of fusion power systems must be realized and effectively communicated to cultivate a positive public perception.
- Regulatory simplicity—substantial efforts in plant design stages should be directed towards minimization of regulatory barriers to commercial fusion deployment.

While global efforts continue to pursue proof of fundamental physics, control, and feasibility of fusion, meaningful and compelling progress has been made in private sector efforts that indicate commercially-relevant demonstrations are imminent and warrant attention from the industry end-user community.

It is with this in mind that EPRI debuted the Fusion Forum in December 2020, as a setting to facilitate discussions among fusion developers and stakeholders. This interest group is intended to align the fusion technology developer community with the utility end-users as fusion draws nearer to demonstration and commercialization, with EPRI serving as a bridge for these groups.

EPRI FUSION RESOURCES:

Assessment of Fusion Energy Options for Commercial Electricity Production (EPRI, 2012, #1025636)

J. Kaslow, M. Brown, R. Hirsch, R. Izzo, J. McCann, D. McCloud, B. Muston, A. Peterson, Jr., S. Rosen, T. Schneider, P. Skrgic, B. Snow. Criteria for Practical Fusion Power Systems: Report from the EPRI Fusion Panel. *Journal of Fusion Energy* **13**(2/3), 1994.

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- **All information in Tables 1 and 2 was sourced from each entity's webpage**.

TECHNICAL CONTACT

Daniel Moneghan, Engineer/Scientist
Nuclear Innovation
Electric Power Research Institute
dmoneghan@epri.com

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com