COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY
U.S. HOUSE OF REPRESENTATIVES
HEARING CHARTER

Fostering a New Era of Fusion Energy Research and Technology Development
Wednesday, November 17, 2021
10:00AM ET

Purpose

The purpose of this hearing is to examine the current status of fusion energy research and development (R&D) activities carried out by the U.S. Department of Energy, the private sector, and internationally. The hearing will also consider next steps for Congress and the Administration to take in response to recent reports from the Fusion Energy Sciences Advisory Committee and the National Academies that provide roadmaps for fusion energy R&D and commercialization pathways over the next decade and beyond.

Witnesses

- **Dr. Troy Carter**, Director, Plasma Science and Technology Institute, University of California, Los Angeles and Chair, Fusion Energy Sciences Advisory Committee Long Range Planning Subcommittee
- **Dr. Tammy Ma**, Program Element Leader for High Energy Density Science, Lawrence Livermore National Laboratory
- **Dr. Robert Mumgaard**, CEO, Commonwealth Fusion Systems
- **Dr. Kathryn McCarthy**, Director, U.S. ITER Project Office
- **Dr. Steven Cowley**, Director, Princeton Plasma Physics Laboratory

Recent Strategic Plans

On February 11th, 2021, the Fusion Energy Sciences Advisory Committee (FESAC) released a strategic plan for the Department of Energy's fusion R&D activities entitled *Powering the Future: Fusion and Plasmas*.[1] This report was the result of a two-year process initiated by the Department, pursuant to statutory direction included in the Department of Energy Research and Innovation Act, which was advanced by the House Committee on Science, Space, and Technology and signed into law on September 28th, 2018.

The report establishes priorities for fusion research, technology development, and facility construction and decommissioning activities over the following ten years under three budget scenarios: constant funding (including inflation but no growth), modest growth (2% above inflation), and unconstrained with prioritization. Under all scenarios, the report recommends: continued support for U.S. participation in the ITER international fusion project; the establishment of an inertial fusion energy research program; support for the development of

[1] https://usfusionandplasmas.org/

alternative and enabling fusion energy concepts and technologies; enhanced support for public-private partnerships; and a range of levels of support for facility construction to examine fusion-relevant materials.

The constant funding scenario in this report would: reduce operations and research at current major facilities; cancel a planned upgrade to a high energy density plasma science facility (referred to as Matter in Extreme Conditions – Upgrade [MEC-U]) at SLAC National Accelerator Laboratory; significantly delay development and construction of a proposed facility called the Fusion Prototypic Neutron Source (FPNS) for materials irradiation research purposes; and prevent development of a proposed facility to examine and address the impacts of high heat fluxes associated with commercial-scale fusion plasmas, called the Exhaust and Confinement Integration Tokamak Experiment (EXCITE).

The unconstrained, though prioritized, funding scenario in this report would: accelerate development and initiation of construction of FPNS; support construction of MEC-U (which is also proposed to be cancelled in the modest growth scenario); support the design and construction of EXCITE and a new advanced stellarator[2] facility; support development of a test facility to address future commercial-scale fusion reactor fueling needs; and support design and development of several other alternative and enabling concept facilities on a prioritized basis to the extent that funding is available. This scenario would also support enhanced research and technology development in inertial fusion energy, alternative concepts, fusion materials, and fundamental plasma science as well as enhanced international collaborations.

Dr. Troy Carter served as Chair of the FESAC Subcommittee that developed this report.

On February 17th, 2021, the National Academies released a report entitled *Bringing Fusion to the U.S. Grid*.[3] This report focused specifically on steps necessary to develop a pilot plant for fusion energy. The primary recommendations of this report were the following:

- "For the United States to be a leader in fusion and to make an impact on the transition to a low-carbon emission electrical system by 2050, the Department of Energy and the private sector should produce net electricity in a fusion pilot plant in the United States in the 2035-2040 timeframe.

- "The Department of Energy should move forward now to foster the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps and lead to an engineering design of a pilot plant that will bring fusion to commercial viability."

Dr. Kathryn McCarthy is a Member of the National Academy of Engineering and served on the National Academies Committee on the Key Goals and Innovation Needed for a U.S. Fusion Pilot Plant, which produced this report.

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[2] https://www.energy.gov/science/doe-explainsstellarators

[3] https://www.nationalacademies.org/news/2021/02/government-and-private-sector-should-produce-net-electricity-in-fusion-pilot-plant-by-2035-2040-to-impact-the-transition-to-a-low-carbon-emission-electrical-system-new-report-says

Recent Breakthroughs

In the summer of 2021, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory and Commonwealth Fusion Systems (CFS), in partnership with the Massachusetts Institute of Technology (MIT), both demonstrated breakthrough achievements relevant to the development of fusion energy.

On August 8, 2021, NIF achieved a fusion energy release of 1.3 megajoules from 1.9 megajoules of incident laser energy on a target of fusion fuel.[4] As summarized in a recent blog post[5] by DOE's Advanced Research Projects Agency – Energy (ARPA-E):

"While the NIF result equals the decades-old record tokamak scientific energy gain of approximately 0.7, it represents a worldwide first for any laboratory fusion experiment in achieving an even higher degree of fusion self-heating, putting it solidly into a regime that fusion scientists call a 'burning plasma.'"

The achievement of a burning plasma is a critical step for the development and operation of any viable fusion energy system. This result is also particularly relevant to confirming the potential promise of inertial fusion energy concepts, discussed further below.

Dr. Tammy Ma is the Program Element Leader for High Energy Density Science on NIF.

ARPA-E also summarized CFS's recent achievement[6] as follows:

"On September 5, 2021, CFS and their partners at the Massachusetts Institute of Technology (MIT) announced a successful test of their 20-tesla toroidal-field model coil, demonstrating that their magnet can actually be constructed from cutting-edge, high-temperature superconductors (HTS). Such a magnet enables tokamaks that are significantly smaller, lower cost, and faster to build than ones based on conventional low-temperature superconductors, such as ITER.

"Based on the 60-plus years of research on tokamak physics and its high level of scientific maturity, CFS is confident that if and when SPARC - their tokamak based on this magnet design - is built, it will achieve a scientific energy gain between 2 and 10, quite possibly within this decade. This would constitute the next major scientific milestone for the tokamak that is expected to accelerate and unleash further engineering efforts toward a pilot-scale fusion demonstration." [7]

Dr. Robert Mumgaard is the CEO of CFS.

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[4] https://www.nytimes.com/2021/08/17/science/lasers-fusion-power-watts-earth.html
[5] https://arpa-e.energy.gov/news-and-media/blog-posts/nifty-and-sparcly-recent-achievements-fusion
[6] https://www.newyorker.com/magazine/2021/10/11/can-nuclear-fusion-put-the-brakes-on-climate-change
[7] https://arpa-e.energy.gov/news-and-media/blog-posts/nifty-and-sparcly-recent-achievements-fusion

Recent Legislation and Executive Action

The Department of Energy Research and Innovation Act was enacted on September 28th, 2018. This law provided substantial direction for DOE's fusion energy research activities, and this direction was significantly augmented through provisions in the Energy Act of 2020, enacted on December 28th of last year.

Collectively, these laws directed DOE Office of Science to: establish and support an inertial fusion energy research and technology development program; establish and support an alternative and enabling concepts program; establish and support a milestone-based fusion energy development program; support fusion reactor system design activities; support and provide sufficient resources for the U.S. participation in the ITER international fusion project to maintain its schedule and minimize total project cost; improve coordination with between the DOE Office of Science's Fusion Energy Sciences (FES) program and innovative fusion energy programs and projects supported by ARPA-E; and produce a 10-year strategic plan, among other activities.

Since the enactment of these laws, the DOE Office of Science has carried out a comprehensive strategic planning process, as noted in the "Recent Strategic Plans" section above, and has established a joint program with ARPA-E to support the development of technologies and advanced materials for fusion energy systems.[8] It has also established a small[9] program called the Innovation Network for Fusion Energy (INFUSE) to enable public-private partnerships with FES. However, the Office has not yet implemented the bulk of the statutory direction it received to establish programs for inertial fusion energy R&D, alternative and enabling concepts, milestone-based development, or fusion reactor system design, nor has it included proposals to do so in the Department's FY 2022 Budget Request. DOE also requested 25% less funding than the Department itself estimated would be required in FY 2022 to maintain the schedule and minimize the total project cost of ITER.[10]

The Committee on Science, Space, and Technology included $1.24 billion in total fusion energy R&D funding and $1.6 billion in total support for fusion facility construction and major items of equipment in text that it advanced for the Build Back Better Act to carry out authorized fusion energy activities on September 9th, 2021.[11]

H.R. 3593, the Department of Energy Science for the Future Act,[12] would extend and expand authorizations for fusion energy activities previously authorized in the Department of Energy Research and Innovation Act and the Energy Act of 2020, including further support for alternative and enabling concepts, inertial fusion energy, fusion system design, advanced

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[8] https://arpa-e.energy.gov/technologies/programs/gamow

[9] The FY 2021 budget for INFUSE is $5 million, and DOE has proposed to increase support for this program to $6 million in FY 2022. The total FY 2021 budget for the Fusion Energy Sciences (FES) program is $672 million, and DOE's total request for FES in FY 2022 is $675 million. The total authorized level for FES in FY 2022, provided in the Energy Act of 2020, is $921 million.

[10] According to data provided by the DOE Office of Science on "Ideal Funding" for facility construction projects.

[11] https://science.house.gov/imo/media/doc/Science%20Committee%20Print.pdf

[12] https://science.house.gov/bills/the-doe-science-for-the-future-act

materials, milestone-based partnerships, and ITER. H.R. 3593 passed the House of Representatives on June 28th, 2021.

Additional Background

What is Fusion?

Fusion is the nuclear process that powers the sun and the stars, and research on creating controlled fusion devices to meet growing demands for new energy sources began in the 1950s. In one type of fusion reaction, two atoms of hydrogen combine together, or fuse, to form an atom of helium. In the process, some of the mass of the hydrogen is converted into energy. The easiest fusion reaction to artificially recreate combines deuterium (a "heavy" form of hydrogen as it includes both a proton and a neutron[13]) with tritium (made up of a proton and two neutrons - the heaviest form of hydrogen found in nature) to make helium and a neutron. Deuterium is plentifully available in ordinary water, and tritium can be produced by combining a fusion neutron with the relatively abundant lithium atom. Thus, if its significant remaining scientific questions and engineering challenges can be overcome, fusion may have the potential to be a practically inexhaustible source of clean energy.

All nuclei in atoms are positively charged, so they have a natural electromagnetic repulsion pushing them apart. This is because, while opposite charges attract, like charges repel. So to induce the fusion process, hydrogen gas is typically heated to very high temperatures (100 million degrees or more) to give the atoms sufficient energy to overcome this repulsion and fuse. In the process the gas becomes ionized, meaning that atomic nuclei and their electrons have too much energy to stay bound to each other as neutrally charged atoms. Thus what is known as a plasma is formed. Plasmas are considered the fourth state of matter, after solids, liquids, and gases. Plasmas are unique from normal gases because large portions of them are either unbound electrons or charged nuclei (ions), so they can be manipulated by electric and magnetic fields. If a very hot plasma is held together (i.e. "confined") long enough, then the sheer number of fusion reactions may produce more energy than what is required to heat the plasma to fusion conditions, generating excess energy that can be used for other applications.

The sun and stars do this with gravity. But because the levels of gravity found inside a star are impossible to attain on Earth, other man-made methods of confinement have been developed. These include *magnetic confinement*, in which a strong magnetic field holds the plasma together for relatively long periods of time while its ions and electrons are heated by microwaves or other energy sources, and *inertial confinement*, in which a small capsule of hydrogen, often frozen, is compressed and heated by intense pressure so quickly that fusion occurs before the deuterium and tritium atoms can fly apart from each other. This level of pressure may be attained by utilizing a powerful laser, a beam of heavy ions, or a very strong pulsed magnetic field.

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[13] See charter for hearing entitled *Investigating the Nature of Matter, Energy, Space, and Time* held on October 1st, 2009 here: http://www.gpo.gov/fdsys/pkg/CHRG-111hhrg52294/pdf/CHRG-111hhrg52294.pdf for further explanation of "protons" and "neutrons", which are the primary constituents of an atom's nucleus.

Magnetic Confinement – ITER and the Tokamak

Most fusion energy research today is focused on the most successful configuration for fusion devices to date, called the tokamak. Tokamaks, first conceived of by Russian scientists in the 1950s, are devices that are essentially toroidally (i.e. doughnut) shaped at their core. External coils induce magnetic fields which wind around the inside of the toroid and confine the hot plasma within. In 1997, a tokamak in England called the Joint European Torus (JET) achieved the world record for the ratio of fusion power produced to input heating power, also known as gain or Q, of 0.7. This record is now approximately matched by recent results on the National Ignition Facility, as discussed in the "Recent Breakthroughs" section above.

ITER is designed to achieve a Q of 10, which is roughly the minimum required gain in a commercial fusion power plant once losses in electricity conversion and transmission are taken into account. Absent an independent breakthrough achievement, ITER would be the first scientific tool for exploring and testing expectations of behavior of a magnetically confined plasma in which the fusion process itself provides the primary heat source to sustain its high temperatures, also called a "burning plasma." A clear and comprehensive understanding of this type of plasma is needed to confidently extrapolate its behavior and related control technologies beyond ITER and toward designing reliable fusion power plants.

The project is being designed and built by the members of the ITER Organization (IO): the European Union (EU), India, Japan, China, Korea, Russia, and the U.S. The device is under construction at Cadarache in southeastern France with the EU serving as the host party, and it is currently expected to begin preliminary operations in December 2025. As of August 31st, 2021, the project's progress toward this milestone was determined to be 74.8% complete.[14] The U.S. is primarily contributing hardware components and personnel during ITER's construction phase, with nearly all of these components being manufactured in the U.S. and then shipped to Cadarache. Throughout this phase, the U.S. is an equal, non-host partner responsible for approximately 9 percent of its total construction cost. (The EU, as the host partner, is responsible for about 45 percent of the cost.) DOE's most recent estimate for the total cost for the U.S. contribution is $4.96 billion.[15] However, the impacts of the COVID-19 pandemic on the DOE Office of Science's various facility construction activities have not yet been fully assessed.

U.S.-Based Magnetic Fusion Facilities

The U.S. currently hosts two major magnetic fusion facilities. One is a tokamak and the other is known as a "spherical torus", which is essentially a uniquely shaped tokamak that, at its core, appears to be a ball with a narrow hole through its center. These facilities include:

- **DIII-D** (pronounced "D. 3. D.")[16] – a tokamak operated by General Atomics in San Diego, CA. It is the largest magnetic fusion facility in the U.S., and geometrically the closest to the ITER configuration. DIII-D has unique capabilities to shape its plasma and provide feedback control of errant magnetic fields that affect the stability of the plasma.

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[14] https://www.iter.org/construction/construction

[15] According to data provided by the DOE Office of Science.

[16] https://www.ga.com/magnetic-fusion/diii-d

- **The National Spherical Torus Experiment – Upgrade**[17] – NSTX-U is operated by the Princeton Plasma Physics Laboratory (PPPL). Its spherical torus configuration may have several advantages over conventional tokamaks, a major one being the potential ability to confine a higher plasma pressure for a given magnetic field strength, which could enable the development of smaller, lower cost fusion reactors. After a malfunction that resulted in damage to the facility in 2016, NSTX-U is currently undergoing repairs.

National Ignition Facility (NIF) and Inertial Fusion Energy

NIF is located at Lawrence Livermore National Laboratory in Livermore, CA, and is the largest inertial fusion facility in the world. Its primary mission is to produce data relevant to ensuring the reliability of the U.S.'s nuclear weapons stockpile through the study of controlled fusion events similar to the detonation of a thermonuclear warhead, and it is therefore wholly supported by DOE's National Nuclear Security Administration (NNSA), not the DOE Office of Science. However, while the facility was not designed for energy research, experiments conducted at NIF have provided scientific and technological insights relevant to the pursuit of inertial fusion for energy applications.

FES has not established a program to support research in inertial fusion for the purposes of energy generation, though a report by the National Academies entitled *An Assessment of the Prospects for Inertial Fusion Energy*[18] found major scientific and technological progress in this fusion path several years prior to the result described above in the "Recent Breakthroughs" section. The report concluded that "[t]he potential benefits of energy from inertial confinement fusion … provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy."

Alternative approaches

In addition to the large-scale tokamak and laser-induced inertial fusion concepts, exemplified by ITER and NIF, respectively, several alternative concepts and smaller scale variations have been pursued over the last five decades. In recent years, several new small and mid-sized start-up companies have emerged proposing innovative fusion energy device configurations which, if successful, could dramatically accelerate the development and deployment of commercial fusion reactors.[19] None are expected to ultimately scale up to a commercial, competitive reactor without more substantial federal support in the research, development, and demonstration phases.

The most prominent recent development in U.S. government support for innovative fusion energy concepts is the establishment of a program called ALPHA[20,21] (Accelerating Low-cost

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[17] https://www.pppl.gov/research/nstx-u
[18] http://www.nap.edu/catalog/18289/an-assessment-of-the-prospects-for-inertial-fusion-energy
[19] https://www.nytimes.com/2021/10/18/business/fusion-energy.html
[20] http://arpa-e.energy.gov/?q=arpa-e-programs/alpha
[21] According to ARPA-E, its $30M investment in projects under the ALPHA program has led to more than $600M in follow-on funding from the private sector to ALPHA projects and spinouts, including Zap Energy (approximately $34 million raised in 2 rounds) and Helion (approximately $570 million raised in multiple rounds). Overall, 5 out of the 9 projects supported by the ALPHA program received follow-on funding from the private sector.

Plasma Heating and Assembly) by ARPA-E in 2015. ALPHA focused on a potentially lower-cost fusion parameter regime that falls between the lower plasma density tokamaks and the very high density laser fusion approaches. This regime is often called “magneto-inertial fusion” because most concepts involve temporarily confining and then imploding a small deuterium-tritium plasma target in a very strong and growing magnetic field.

Last year, ARPA-E established a successor program called BETHE[22] (Breakthroughs Enabling THermonuclear-fusion Energy, acronym pronounced *Beta*), which significantly broadened the range of innovative fusion energy concepts and enabling technologies supported by the agency. However, the duration of these programs is limited to approximately 3 years, like nearly all other ARPA-E programs. Therefore, any concept or technology that is determined to be promising, but would require additional federal support to continue its development, would likely need to seek such funding from FES.

Other alternative concepts that may be viable include the stellarator and the high magnetic field compact tokamak. Stellarators[23] are shaped more like pretzels (or, more accurately, French crullers[24]) than doughnuts, with the non-symmetric, three-dimensional shape precisely designed and engineered using advanced computational models to make a magnetic field topology that can indefinitely contain a fusion plasma with minimal disruptions. The largest stellarator in the world, Wendelstein 7-X[25] in Greifswald, Germany, began scientific operations in February 2016. A three-lab American consortium, including PPPL, Oak Ridge, and Los Alamos National Laboratory, is partnering with this project.

The high magnetic field compact tokamak concept developed by Commonwealth Fusion Systems, in partnership with MIT, more directly builds on the large body of well-understood tokamak research results to date, but would take significant advantage of recently commercialized, lower cost superconducting materials that operate at higher temperatures than the materials used in ITER. As discussed in the “Recent Breakthroughs” section above, this may allow for a much smaller scale commercial tokamak device with far lower capital costs than believed possible given the engineering limits that the previous generation of superconductors imposed.

[22] https://arpa-e.energy.gov/technologies/programs/bethe
[23] https://www.energy.gov/science/doe-explainsstellarators
[24] https://www.thedonutmanca.com/wp-content/uploads/2012/07/Glazed-French-Cruller.jpg
[25] https://www.ipp.mpg.de/16900/w7x