FOSTERING A NEW ERA OF FUSION ENERGY RESEARCH AND TECHNOLOGY DEVELOPMENT

HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

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CONTENTS

November 17, 2021

Opening Statements

Witnesses:

Appendix: Answers to Post-Hearing Questions

FOSTERING A NEW ERA OF FUSION ENERGY RESEARCH AND TECHNOLOGY DEVELOPMENT

WEDNESDAY, NOVEMBER 17, 2021

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10:02 a.m., via Zoom, Hon. Jamaal Bowman [Chairman of the Subcommittee] presiding.

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

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[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.

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[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

Chairman BOWMAN. Good morning, everyone. This hearing will come to order. Without objection, the Chairman is authorized to declare recess at any time.

Before I deliver my opening remarks, I wanted to note that, today, the Committee is meeting virtually. I want to announce a couple of reminders to the Members about the conduct of this hearing. First, Members should keep their video feed on as long as they are present in the hearing. Members are responsible for their own microphones. Please also keep your microphones muted unless you are speaking. Finally, if Members have documents they wish to submit for the record, please email them to the Committee Clerk, whose email address was circulated prior to the hearing.

Good morning, and thank you to this excellent panel of witnesses who are joining us virtually today to discuss recent breakthroughs and next steps for the Department of Energy's (DOE's) fusion energy research activities. As our witnesses will be able to discuss in much more detail, fusion is the process that powers the Sun and the stars. It is a simple fact that this fundamental phenomenon is essential to the existence of vital renewable energy sources like solar and wind energy, and indeed to life on Earth.

For many decades, top scientists around the globe have worked to find ways to replicate the conditions enabled by the immense sheer gravity inside the core of a star to harness this potentially limitless source of clean energy more directly. There have been challenges and setbacks along the way, and significant challenges remaining on the path toward realizing this transformative goal. But we now have new reasons for hope, as well as comprehensive roadmaps driven by the research community to guide us on this path.

On August 8th this past summer, the National Ignition Facility (NIF) at DOE's Lawrence Livermore National Laboratory (LLNL) produced the first so-called "burning plasma" in a manmade experiment. A burning plasma is a condition in which the fusion process itself provides the primary heat source to sustain the fuel's high temperatures that keep the fusion process going. The achievement of a burning plasma is a critical step for the development of any viable fusion energy system.

And on September 5th, less than a month later, Commonwealth Fusion Systems (CFS) and its partners at MIT (Massachusetts Institute of Technology) achieved a successful test of a high-temperature superconducting (HTS) magnet up to a field strength of 20 tesla, the most powerful magnetic field of its kind ever created on Earth. Such a magnet could enable fusion systems that are significantly smaller, lower cost, and faster to build than what was previously thought possible.

I am also pleased to highlight that the fusion research community has stepped up in recent years to produce a long-range strategic plan, which this Committee had directed the Department of Energy to initiate in the *DOE Research and Innovation Act* that was enacted in 2018. It is important for us in Congress to have a far better understanding of how the community would prioritize research activities and facility construction plans under a range of plausible budget scenarios. I recognize that tough decisions were made by the community in carrying out this effort, and hope that this hard and thorough work is better recognized in DOE's forthcoming budget requests for these programs.

Thank you all again, and I look forward to this discussion.

[The prepared statement of Chairman Bowman follows:]

Good morning, and thank you to this excellent panel of witnesses who are joining us virtually today to discuss recent breakthroughs and next steps for the Department of Energy's fusion energy research activities.

As our witnesses will be able to discuss in much more detail, fusion is the process that powers the sun and the stars. It is a simple fact that this fundamental phenomenon is essential to existence of vital renewable energy sources like solar and wind energy, and indeed to life on earth. For many decades, top scientists around the globe have worked to find ways to replicate the conditions enabled by the immense, sheer gravity inside the core of a star to harness this potentially limitless source of clean energy more directly.

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Thank you all again, and I look forward to this discussion.

Chairman BOWMAN. With that, I now recognize Mr. Weber for an opening statement.

Mr. WEBER. Thank you, Chairman Bowman, for holding this hearing, and thank you to our witness panel for joining us this morning. Today's topic is one that many of us are very familiar with, but we remain extremely intrigued by: fusion energy.

In the most basic of terms, fusion energy aims to create the equivalent of a controlled Sun and harness it as a power source here on Earth. Easy enough, right? But as you might imagine, the extreme temperatures, pressures, and confinement conditions required to do this also require a highly specialized environment. This makes achieving fusion energy one of the greatest challenges in experimental physics today.

The potential benefits of a fusion reactor are beyond calculation. The fuel is abundant and widely accessible, the carbon footprint is functionally zero, and the radioactive waste concerns are almost nonexistent. If we are serious about a clean energy future with low power sector emissions, there is no ambition that fits that bill better than fusion.

The Department of Energy supports fusion R&D (research and development) primarily through its Fusion Energy Sciences, or

FES, program. In Fiscal Year 2021, the FES received $672 million, but the House-passed bipartisan bill that I was proud to cosponsor, the *DOE Science for the Future Act,* seeks to nearly double that by Fiscal Year 2026. This shows our overwhelming support for current research efforts and a bipartisan desire to leverage the untapped potential of fusion. I'd like to thank my colleague, Energy Subcommittee Chairman Bowman, as well as Ranking Member Lucas and Chairwoman Johnson, for their leadership on this bill.

Domestically, DOE funds a diverse portfolio of fusion energy research through its world-leading national laboratory system and cutting-edge experimental facilities and resources, like the National Spherical Torus Experiment Upgrade at Princeton Plasma Physics Laboratory (PPPL) and the National Ignition Facility at Lawrence Livermore National Laboratory. I look forward to hearing from esteemed representatives from these laboratories today.

Internationally, DOE supports U.S. contributions to the ITER (International Thermonuclear Experimental Reactor) project, which many of you know is a major international collaboration to design, build, and operate a first-of-a-kind research facility to achieve and maintain a successful fusion reaction in the lab. Although it is located in beautiful southern France, a significant percentage of total U.S. awards and obligations to ITER are carried out—pardon me—right here in the United States, funding research and component fabrication in American universities, national labs, and in industry. And while the United States contributes 13 percent of the cost of ITER, we will actually gain 100 percent of the scientific discoveries from this project. That's a good tradeoff, a good deal in my estimation.

This is why funding for ITER is also included in the *DOE Science for the Future Act.* Upholding our end of this deal is imperative to the success of U.S. fusion energy and to America's standing and credibility as a global scientific collaborator, excuse me. I look forward to hearing more on this from Dr. Kathryn McCarthy, the Director of the U.S. ITER Project Office—as our lights go out here. If we get fusion on board quickly now, we won't have that problem. Did I mention we were working on that Chairman Bowman?

Another necessary contributor to fusion research is, of course, the private sector. Due to robust DOE investment in this critical science, there are already 13 fusion energy companies here in the United States. Today, we will hear from one of these companies, Commonwealth Fusion Systems, a startup aimed at commercializing fusion energy and has collaborated with the National Labs through FES's Innovation Network for Fusion Energy, or the INFUSE program. Together, our witness panel represents unique areas of fusion energy research. They each have a story to tell on how we've progressed over the last decade and where we are headed in the next decade.

No matter how you look at it, achieving commercial fusion energy technology is going to require strong U.S. leadership and consistent investment in discovery science. Meeting our goal of producing unlimited emission-free power through fusion energy will truly take all of you here today.

I want to again thank again our witnesses for being here today and yield back the balance of my time, Mr. Chairman. Thank you.

[The prepared statement of Mr. Weber follows:]

Thank you, Chairman Bowman for holding this hearing and thank you to our witness panel for joining us this morning. Today's topic is one that many of us are very familiar with, but we remain extremely intrigued by—fusion energy.

In the most basic of terms, fusion energy aims to create the equivalent of a controlled sun and harness it as a power source here on earth. Easy enough, right? But as you might imagine, the extreme temperatures, pressures, and confinement conditions required to do this also require a highly specialized environment. This makes achieving fusion energy one of the greatest challenges in experimental physics today.

The potential benefits of a fusion reactor are beyond calculation. The fuel is abundant and widely accessible, the carbon footprint is functionally zero, and the radioactive waste concerns are almost nonexistent. If we are serious about a clean energy future with lower power sector emissions, there is no ambition that fits the bill better than fusion.

The Department of Energy supports fusion R&D primarily through its Fusion Energy Sciences program. In fiscal year 2021, the FES received $672 million, but the House passed bipartisan bill I was proud to cosponsor, the *DOE Science for the Future Act,* seeks to nearly double that by fiscal year 2026.

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This is why full funding for ITER is also included in the *DOE Science for the Future Act.* Upholding our end of this deal is imperative to the success of U.S. fusion energy, and to America's standing and credibility as a global scientific collaborator. I look forward to hearing more on this from Dr. Kathryn McCarthy, the Director of U.S. ITER Project Office.

Another necessary contributor to fusion research is, of course, the private sector. Due to robust DOE investment in this critical science, there are already 13 fusion energy companies are here in the U.S. Today we will hear from one of these companies—Commonwealth Fusion Systems, a startup aimed at commercializing fusion energy and has collaborated with the National Labs through FES's Innovation Network for Fusion Energy (INFUSE) program.

Together, our witness panel represents unique areas of fusion energy research. They each have a story to tell on how we've progressed over the last decade and where we are headed in the next.

No matter how you look at it, achieving commercial fusion energy technology will require strong U.S. leadership and consistent investment in discovery science. Meeting our goal of producing unlimited, emission free power through fusion energy will truly take all of you here today. I want to again thank all of our witnesses for being here and yield back the balance of my time, Mr. Chairman.

Chairman BOWMAN. Thank you, Mr. Weber.

The Chair now recognizes the Chairwoman of the Full Committee, Ms. Johnson, for an opening statement.

Chairwoman JOHNSON. Thank you very much, and good morning to all. I appreciate you holding this hearing on fusion energy activities carried out by the Department of Energy.

There are many of us on the Science, Space, and Technology Committee on both sides of the aisle that strongly believe that the promise of fusion energy is worth pursuing, and for that matter, warrants far greater support than the Federal Government has provided to date. Fusion has been the potential to deliver clean and abundant energy to the world, all while producing essentially no greenhouse gas emissions.

I have previously noted that a breakthrough in fusion energy research would be a major step in enabling our clean energy future. And in fact there has been a couple of significant breakthroughs within the last few months, so I am pleased that we have witnesses here today who will discuss those in detail. And though there is still more work that needs to be done, the policy decisions and research investments we make now could well enable the next key advancements to come much sooner.

Fusion energy research has had a longstanding support from the Science Committee. I am proud to say that over the past few years, this Committee has advanced numerous bills that provide significant direction for fusion research activities supported by the Department of Energy. These include substantial provisions in the *Department of Energy Research and Innovation Act* as well as the *Energy Act of 2020,* both of which were signed into law.

In June, the House passed the *Department of Energy Science for the Future Act,* a bill that I lead with Ranking Member Lucas and both Chairman Bowman and Ranking Member Weber of the Energy Subcommittee. This bill would expand upon previously authorized fusion energy activities, including strong authorization of appropriations for these programs. It includes full support for U.S. participation in ITER international fusion project. And I would say that Congressman Lucas and I have visited that project.

And I would be remiss if I did not note that this Committee included $1.24 billion in total funding for fusion energy R&D and $1.6 billion in total support for fusion facility construction and equipment in the text that it advances for the *Build Back Better Act.*

I was also pleased to see the recent reports released by both the Fusion Energy Sciences Advisory Committee (FESAC) and the National Academies. These reports outline strategic investments needed to enable a robust national fusion research program, including steps required to develop a pilot plant for fusion energy.

Despite all of this progress made by Congress and the fusion research community, the Department of Energy has yet to implement much of the guidance provided by these external advisory reports, nor has DOE implemented much of the direction provided in law. We need to do better, especially at this time when there is so much more work to be done in this field.

I very much look forward to the testimony today from this panel of distinguished witnesses. And with that, Mr. Chairman, I yield back.

[The prepared statement of Chairwoman Johnson follows:]

Good morning and thank you, Chairman Bowman, for holding this hearing on fusion energy activities carried out by the Department of Energy. There are many of us on the Science, Space, and Technology Committee on both sides of the aisle that strongly believe that the promise of fusion energy is worth pursuing, and for that matter, warrants far greater support than the federal government has provided to date.

Fusion has the potential to deliver clean, abundant energy to the world, all while producing essentially no greenhouse gas emissions. I have previously noted that a breakthrough in fusion energy research would be a major step in enabling our clean energy future. And in fact, there have been a couple of significant breakthroughs within the last few months, so I am pleased that we have witnesses here today who will discuss those in detail. And though there is still more work that needs to be done, the policy decisions and research investments we make now could well enable the next key advancements to come much sooner.

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I very much look forward to the testimony today from this panel of distinguished experts. With that, I yield back.

Chairman BOWMAN. Thank you so much for your remarks, Chairwoman Johnson.

The Chair now recognizes the Ranking Member of the Full Committee, Mr. Lucas, for an opening statement.

Mr. LUCAS. Thank you, Chairman Bowman.

Today, we have an opportunity to examine the status of fusion energy research in the United States. I look forward to hearing more about how we can provide robust support for these high-priority research activities both internationally and here at home.

Fusion R&D has long enjoyed bipartisan support on the Science Committee and for good reason. It is exactly the type of high-risk, high-reward basic research that expands our fundamental knowledge of science and technology and pushes the limits of what is possible. Fusion energy has the potential to produce discoveries that will transform our clean energy future, keeping America energy-independent and at the same time the cutting edge of technological progress.

To realize the promise of fusion energy, we must take an all-of-the-above approach. We must support full funding for U.S. participation in ITER—the leading international research project for fusion energy—and we must make major investments in DOE national laboratories like Princeton's Plasma Physics Laboratory and Lawrence Livermore's National Laboratory, and we must support productive partnerships with the rapidly growing U.S. fusion energy industry.

Last Congress, we passed the *Energy Act of 2020,* which includes significant authorizations of DOE's Fusion Energy Science activities, including an inertial fusion R&D program, fusion reactor system design activities, an Innovation Network for Fusion Energy, and explicit direction for U.S. participation in ITER.

Our bill, H.R. 3593, the *Department of Energy Science for the Future Act,* will build on the success of the *Energy Act.* Like that bill, *DOE Science for the Future Act* is overwhelmingly bipartisan. It's the product of years of hearings and discussions with stakeholders. The *DOE Science for the Future Act* is the first comprehensive authorization of the DOE Science—Office of Science. This legislation will invest $50 billion over 5 years, giving the Office of Science and our National Laboratories the resources they need to continue to excel.

This landmark legislation includes more than $5.6 billion for Fusion Energy Sciences, extending and supplementing authorizations in the *Energy Act.* But it's not simply an authorization of research dollars. This legislation provides essential policy direction and strategic guidance for U.S. fusion energy R&D based on extensive stakeholder feedback and reports from the Fusion Energy Sciences Advisory Committee and the National Academies. This is a thoughtful, well-vetted, overwhelmingly bipartisan bill designed to significantly improve American research and development.

The House approach to competitiveness legislation has been thoughtful, deliberate, and strategic. It makes smart investments to make continuous improvements to American research and development. So as discussions are starting about incorporating competitiveness legislation into the *NDAA (National Defense Authorization Act),* I believe it's critical our priorities are included.

This Congress, we've seen a lot of multi-trillion-dollar spending proposals come and go. We've heard a lot about so-called opportunities to cut corners and to heavily compromise on our shared principles. The best path forward for fusion energy legislation is the *DOE Science for the Future Act.* We can't afford to accept—let's just be blunt about it—the Senate's half-baked proposal, and we can't afford to accept a social engineering bill with a fraction of our fusion energy investments, stripped of policy direction and long-term planning.

I appreciate Chairman Johnson and Chairman Bowman's commitment to our shared goal of strengthening our investment in fusion energy, and I look forward to working together to get this bill signed into law.

I want to thank our witnesses for their testimony today and for outlining their plans to make fusion energy a reality for the next generation. I look forward to a productive discussion. And I thank you, Chairman Bowman, and I yield back the balance of my time.

[The prepared statement of Mr. Lucas follows:]

Thank you, Chairman Bowman.

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I appreciate Chairwoman Johnson's and Chairman Bowman's commitment to our shared goal of strengthening our investment in fusion energy and I look forward to working together to get this bill signed into law.

I want to thank our witnesses for their testimony today, and for outlining their plans to make fusion energy a reality for the next generation. I look forward to a productive discussion. Thank you, Chairman Bowman, I yield back the balance of my time.

Chairman BOWMAN. Thank you, Ranking Member Lucas, for your remarks.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

At this time I would like to introduce our witnesses. Dr. Troy Carter is a Professor of Physics and the Director of the Plasma Science and Technology Institute at the University of California, Los Angeles (UCLA). He chaired the long-range planning subcommittee of the DOE Office of Science's Fusion Energy Sciences Advisory Committee. Professor Carter is also the Director of the Basic Plasma Science Facility, a collaborative research facility for fundamental plasma science supported by DOE and NSF (National Science Foundation). His research focuses on experimental studies and magnetized plasmas.

Dr. Tammy Ma is the Program Element Leader for High-Intensity Laser High Energy Density Science at the National Ignition Facility at Lawrence Livermore National Laboratory. This group pioneered the use of the highest intensity lasers in the world to investigate novel states of matter, study laboratory astrophysics, and explore fusion physics.

Dr. Robert Mumgaard is the CEO (Chief Executive Officer) of Commonwealth Fusion Systems. CFS is a private commercial fusion company with the goal of commercializing a high magnetic field approach to fusion. Dr. Mumgaard performed his Ph.D. work at MIT where he substantially contributed to the development of this approach.

Dr. Kathryn McCarthy is a U.S. ITER Project Director, as well as Associate Laboratory Director for Fusion and Fission Energy and Science at Oak Ridge National Laboratory (ORNL). She served on the Fusion Energy Sciences Advisory Committee from 1999 to 2013 and on the U.S. ITER Technical Advisory Committee from 2010 to 2013 and has held numerous leadership positions in the American Nuclear Society. Dr. McCarthy joined Oak Ridge National Laboratory after 3 years at Laboratory Director—as laboratory Director for the Canadian Nuclear Laboratories. She previously held a variety of engineering and leadership roles at Idaho National Laboratory.

Dr. Steven Cowley is the seventh Director of the Princeton Plasma Physics Laboratory and a Princeton Professor of Astrophysical Sciences. Prior to joining PPPL, he was President of Corpus Christi College and a Professor of Physics at the University of Oxford. Dr. Cowley previously was Chief Executive Officer of the United Kingdom Atomic Energy Authority and head of the Culham Centre for Fusion Energy. From 2011 to 2017 he was a member of the U.K. Prime Minister's Council on Science and Technology and was even knighted by the Queen of England in 2018. So we should actually call you Sir Dr. Steven Cowley, my apologies, sir.

Thank you all for joining us today. As our witnesses should know, you will each have 5 minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. When you all have completed your spoken testimony, we will begin with questions. Each Member will have 5 minutes to question the panel.

We will start with Dr. Carter. Dr. Carter, please begin.

TESTIMONY OF 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. CARTER. Thank you. Chairman Bowman, Ranking Member Weber of the Subcommittee, Chairwoman Johnson and Ranking Member Lucas of the Full Committee, and distinguished Members of the Committee, thank you for holding this hearing and for providing me and my colleagues with the opportunity to testify. My name is Troy Carter. I'm the Director of the Plasma Science and Technology Institute and Professor of Physics at UCLA. I serve on the DOE Office of Science's Fusion Energy Sciences Advisory Committee, or FESAC. I'm speaking today in my capacity as an academic researcher. I'm not here to formally represent UCLA or FESAC.

As was already mentioned, I recently chaired a FESAC subcommittee that was charged with developing a long-range plan for fusion energy and plasma science research for DOE. The resulting consensus report, "Powering the Future Fusion and Plasmas," was a result of a 2-year strategic planning process with strong engagement from the entire research community, including universities, national labs, and industry. The report represents a 10-year strategy for both fusion energy development and for advancing plasma science and related technologies. I'll focus my brief comments here on fusion energy strategy in that report. I'd be happy to take questions on broader plasma science and engineering.

The main message I want you to take away from my remarks is that now is the time to move aggressively toward the development and deployment of fusion energy. Fusion will provide carbon-free, safe electricity generation that can substantially power society and mitigate climate change.

Why are we confident that now is the right time? There's been important scientific and technological process, coupled with a strongly growing private sector, that positions us to realize a unique U.S. vision for economical fusion energy with the goal of an electricity-producing fusion pilot plant. This unique vision was first laid out in the 2019 National Academies report, "A Strategic Plan for U.S. Burning Plasma Research," as endorsed by our FESAC report and also by the 2021 National Academies report "Bringing Fusion to the U.S. Grid." The strong support for fusion energy research, including from this Committee and Congress—thank you—has enabled important recent scientific progress and breakthroughs. Several examples of this progress is outlined in our report, for example, advances in our understanding of fusion plasmas, achieving new performance records.

They will also be brought up by Professor Cowley in this hearing. He'll offer a few highlights that have occurred since the report was published, and a couple of them have already been brought up in the opening remarks. First is the recent breakthrough at the National Ignition Facility just this past summer where record gain was achieved, and this was enabled by recently acquired scientific understanding. Dr. Ma will discuss this very important result.

Second is the recent demonstration by Commonwealth Fusion Systems of a high-temperature superconducting or HTS magnet, the largest of its kind in the world, operating at 20 tesla that was mentioned earlier. Dr. Mumgaard will discuss this breakthrough that is really a gamechanger for fusion.

Finally, there's been important progress with the international ITER project with the delivery of the first two magnet modules for the ITER central solenoid. This solenoid will be the largest low-temperature superconducting magnet in the world, and Dr. McCarthy will talk more about this achievement of the U.S. ITER Project Office that she leads and General Atomics.

Alongside this technical promise—progress, we've seen rapid growth of private sector investment in fusion energy. The ultimate goal of fusion energy research in the United States is the development of a commercial fusion power industry, and that industry is already taking root. At the time of the writing of our report, about $2 billion had been invested worldwide in fusion energy development in the private sector, resulting in the largest of several startup fusion companies. There's been new investment since with just half—just in the last few weeks half a billion more announced, and more is coming. This investment has enabled the startup companies to make impressive progress on development of new fusion facilities and create enabling technologies such as the HTS magnet, as I mentioned earlier.

The scientific progress and technical know-how developed through the Federal program enabled the founding of these companies, and we now have the opportunity to amplify Federal investment through partnering. Through this partnership, we can accelerate the timeline and reduce the cost to develop fusion electricity. If we look at our international colleagues, in the U.K. and China there's already a lot of money flowing through—into such partnership programs, and they've successfully attracted private fusion companies through that investment. It's imperative that the United States develops and implements new models, strengthens existing ones for partnership between the public and private sectors.

The consensus FESAC long-range planning report makes recommendations for actions that DOE should take to reorient the fusion program toward the rapid development of fusion energy. It enumerates and prioritizes urgently needed research programs and experimental facilities.

This Committee and Congress had implored our community to come together and create a new strategic plan for fusion. We've now answered that charge and speak with one voice in support of the resulting strategic plan. Now is the time to act. We need to implement the plan.

I want to thank this Committee for authorization language in the *Science for the Future Act* and in the current reconciliation bill that was well-aligned with priorities expressed in our report. We're ready to get to work on making fusion power a reality and look forward to DOE implementing our plan. I look forward to answering your questions. Thank you.

[The prepared statement of Dr. Carter follows:]

Written Testimony of Prof. Troy Carter
Director, Plasma Science and Technology Institute
Professor, Department of Physics and Astronomy
University of California, Los Angeles

Delivered to the
Committee on Science, Space, and Technology
Subcommittee on Energy
United States House of Representatives

Hearing on *Fostering a New Era of Fusion Energy Research and Technology Development*
November 17, 2021

Chairman Bowman, Ranking Member Weber, and Members of the Committee, thank you for holding this hearing and providing me and my colleagues with the opportunity to testify. My name is Troy Carter, and I am the Director of the Plasma Science and Technology Institute and a Professor in the Department of Physics and Astronomy at UCLA. I serve on the DOE Office of Science's Fusion Energy Sciences Advisory Committee (FESAC). I am speaking today in my capacity as an academic researcher and am not here to formally represent FESAC or UCLA.

I recently chaired a FESAC subcommittee that was charged with developing a Long Range Plan for Fusion Energy and Plasma Science research for the Department of Energy Fusion Energy Sciences. The resulting consensus report, *Powering the Future: Fusion and Plasmas*[1], was the result of a two-year strategic planning process with strong engagement from the entire research community, including universities, national labs and industry. The report presents a 10-year strategy for both fusion energy development and for advancing plasma science and related technologies. Fusion and plasma research are inextricably intertwined. In fusion reactions, which power the stars, light nuclei (e.g. hydrogen isotopes) merge to form heavier nuclei (e.g. Helium) and energy is released. In a star, and in fusion reactors on Earth, the fusion fuel is in the plasma state: a super-heated, ionized gas. Advances in fundamental plasma physics are central to the progress that has been made toward realizing fusion energy on Earth. The link between fusion and plasmas is strong but does not fully define either one. Fusion energy requires research into and development of materials that can survive the extreme conditions of a fusion reactor, into technologies for breeding fusion fuel, and into enabling technologies such as magnets. The field of plasma science and engineering is intellectually diverse, is highly interdisciplinary, and has myriad applications beyond fusion energy. I will focus my brief comments here on the fusion energy strategy outlined in the report, but I would be happy to take questions on broader plasma science and engineering.

The main message of my remarks is that *now is the time* to move aggressively toward the development and deployment of fusion energy. Fusion energy will provide carbon-free, safe electricity generation that can substantially power society and mitigate climate change. Why are we confident that now is the right time? Important scientific and technological progress, coupled with a strongly growing private sector, positions us to realize a unique US vision for economical fusion energy with the goal of an electricity-producing fusion pilot plant. This unique US vision was first laid out in the 2019 National

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[1] https://usfusionandplasmas.org

Academies of Sciences, Engineering, and Medicine (NASEM) report *A Strategic Plan for US Burning Plasma Research*[2] and is endorsed by our report and also by the 2021 NASEM report *Bringing Fusion to the US Grid*[3].

The strong and steady support for fusion energy research, including from this committee and Congress, has enabled important recent scientific progress and breakthroughs. Several examples of important progress, e.g. advances in our understanding of fusion plasmas and achievement of new performance records, are discussed in the report and will also be discussed in this hearing by Prof. Cowley. Here I'll offer two highlights that have occurred since the report was published. First is the recent breakthrough at the National Ignition Facility, just this past summer, where extremely high fusion gain was achieved, enabled by recently acquired scientific understanding. Dr. Ma will discuss this very important result. Second is the recent demonstration by Commonwealth Fusion Systems of a high-temperature superconducting (HTS) magnet, the largest in the world, operating at 20T (about 10x stronger than a typical MRI magnet). Dr. Mumgaard will discuss this breakthrough that is a game-changer for fusion.

Alongside this technical progress, we've seen rapid growth of private-sector investment in fusion energy. The ultimate goal of fusion energy research in the US is the development of a US commercial fusion power industry and that fusion energy industry is already taking root. At the time of the writing of our report about $2B had been invested worldwide in fusion energy development in the private sector, resulting in the launch of several start-up fusion energy companies. Significant new investment has occurred since, with $0.5B of new funding announced just in the last few weeks. This investment has enabled start-up companies to make impressive and rapid progress on the development of new fusion demonstration facilities and to create advanced enabling technologies for fusion such as the recent HTS magnet demonstration. The scientific progress and technical know-how developed through the federally-supported research program enabled the founding of these startup companies and we now have the opportunity to amplify federal investment through partnering with the private sector. Through partnership, we can accelerate the timeline to and reduce the cost of developing fusion electricity. Internationally, the United Kingdom and China have already established multi-hundred-million-dollar partnership programs and, through them, have successfully attracted private fusion energy companies. It is imperative that the US develops and implements new models, and strengthens existing ones, for partnerships between the public and private sectors to accelerate the development of fusion power in the US. This is critical to maintain a leadership position in the emerging fusion energy industry.

The consensus FESAC long range planning report makes recommendations for actions that DOE should take to re-orient the US fusion research program toward the rapid development of fusion energy. It enumerates and prioritizes urgently needed research programs and experimental facilities. The report recommends continued and strengthened partnership with the private sector and with our international colleagues, especially through the ITER project that Dr. McCarthy will discuss. This committee and Congress had implored our community to come together and create a new strategic plan for fusion. We

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[2] National Academies of Sciences, Engineering, and Medicine. 2019. Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research. Washington, DC: The National Academies Press. https://doi.org/10.17226/25331.

[3] National Academies of Sciences, Engineering, and Medicine. 2021. Bringing Fusion to the U.S. Grid. Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

have now answered that charge and speak with one voice in support of the resulting strategic plan. Now is the time to act: *we need to implement the plan.* I want to thank this committee for authorization language in the "DOE Science for the Future Act" and language in the current reconciliation bill that is well aligned with the priorities expressed in our report. We're ready to get to work on making fusion power a reality and look forward to DOE implementing our plan. I look forward to answering your questions. Thank you.

TROY CARTER is a Professor of Physics and the Director of the Plasma Science and Technology Institute at the University of California, Los Angeles. Prof. Carter is also the Director of the Basic Plasma Science Facility (BaPSF), a collaborative research facility for fundamental plasma science supported by DOE Fusion Energy Sciences and NSF. His research focuses on experimental studies of fundamental processes in magnetized plasmas and is motivated by current issues in magnetic confinement fusion energy research and in space and astrophysical plasmas including magnetic reconnection, turbulence and transport in magnetized plasmas, heating and current drive by plasma waves and the nonlinear physics of Alfvén waves. He currently serves on the DOE Office of Science's Fusion Energy Advisory Committee (FESAC). He was a co-recipient of the 2002 APS John Dawson Award for Excellence in Plasma Physics Research and is a Fellow of the APS. Prof. Carter received BS degrees in Physics and Nuclear Engineering from North Carolina State University in 1995 and a PhD in Astrophysical Sciences from Princeton University in 2001.

Chairman BOWMAN. Thank you, Dr. Carter.

Dr. Ma, you're now recognized.

TESTIMONY OF DR. TAMMY MA, PROGRAM ELEMENT LEADER FOR HIGH ENERGY DENSITY SCIENCE, LAWRENCE LIVERMORE NATIONAL LABORATORY

Dr. MA. Thank you. Chairman Bowman, Ranking Member Weber of the Subcommittee, Chairwoman Johnson, Ranking Member Lucas of the Full Committee, and all Members of the Committee, thank you for the opportunity to appear before you today to offer testimony on fostering a new era of fusion energy research.

I'm the Program Element Leader for High Intensity Laser High Energy Density Science at the National Ignition Facility at the Lawrence Livermore National Lab. I have submitted my full statement to the Committee, which I ask to be made part of the hearing record. If I may, I will now summarize in a brief opening statement.

The National Ignition Facility, or NIF, is the world's largest, most energetic laser housed in a football stadium-sized facility. The 192 very energetic laser beams of NIF are focused onto a miniature capsule the size of a BB containing fusion fuel. The lasers heat and compress the fuel to conditions hotter and denser than those found at the center of the Sun. The goal is ignition, more energy out than we put in with the lasers.

This past August, a breakthrough fusion yield of 1.35 megajoules was achieved on the NIF, more than 2/3 of the 1.9 megajoules of the laser energy going in. This equates to an energy gain of 70 percent of that needed for ignition and represents a 25X improvement over experiments from a year ago.

The tremendous progress over previous results were made possible by numerous experiments, advances in diagnostics and targets, improved laser precision, overall better understanding of the fusion physics, and a very dedicated team of individuals. This result now places NIF on the threshold of fusion ignition in the laboratory for the first time and demonstrates the feasibility of laboratory-scale laser-driven inertial confinement fusion (ICF) to achieve high fusion yield conditions.

While the central mission of the NIF is to provide experimental insight and data for the National Nuclear Security Administration's (NNSA's) science-based Stockpile Stewardship Program, these same fusion plasmas that we create for national security applications can also be exploited to be the basis of a future clean power source by inertial fusion energy (IFE).

Developing an economically attractive approach to fusion energy is a grand scientific and engineering challenge. It is without a doubt a monumental undertaking, but the potential payoff is even greater: clean, limitless, reliable energy that can not only help address the urgent issue of climate change but can also provide energy sovereignty and security for the United States. The profound benefit to future humanity impels us to support a vigorous and sustained research program into fusion with a diverse portfolio that maximizes our potential pathways to success.

Inertial fusion energy is one such innovative approach with significantly different technological risks to mainstream magnetic fusion energy research. With the recent game-changing results on the NIF and our decades of expertise in inertial fusion science and technology, the United States is well-poised to lead and capitalize on the potential of inertial fusion. However, there is currently no inertial fusion energy program in the United States, and it is not part of a long-term energy R&D portfolio but should be.

A number of promising technologies key to eventual inertial fusion energy systems are already making steady progress. In particular, there have been exciting advances in high-energy rep.-rated laser and pulsed power technology in the United States, potentially lowering the cost for a future driver for a fusion energy system.

Additive and advanced manufacturing are revolutionizing new materials and techniques critical to fusion energy. Artificial intelligence and machine learning are being deployed to train high-performance computational models and improve prediction—predictive simulation capabilities. The National Academy of Sciences in 2013 released a report entitled "An Assessment of the Prospects for Inertial Fusion Energy." Amongst the many excellent recommendations was that the appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved. This is the time to begin as we stand at that threshold.

Inertial fusion energy is a multi-decadal endeavor, and realizing it will not be easy. It will require the best minds and bold leadership. But it is a worthy challenge. And that is exactly where we as a nation excel. Now is the time to reestablish a vibrant national inertial fusion energy program and ignite a credible development path toward clean fusion energy.

Thank you for your time. I look forward to your questions.

[The prepared statement of Dr. Ma follows:]

Written Testimony of Dr. Tammy Ma
Program Element Leader for High-Intensity Laser High Energy Density Science, National Ignition Facility & Photon Science
Lawrence Livermore National Laboratory

Delivered to the
Committee on Science, Space, and Technology Subcommittee on Energy
United States House of Representatives

Hearing on *Fostering a New Era of Fusion Energy Research and Technology Development*
November 17, 2021

Chairman Bowman, Congressman Weber, and Members of the Committee, thank you for the opportunity to testify before you today about fusion energy. My name is Tammy Ma, and I am currently the Program Element Leader for High-Intensity Laser High Energy Density Science at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). I have been involved in inertial confinement fusion (ICF) experiments on the NIF since experimental campaigns commenced on the facility in 2009, and I currently serve on the DOE Office of Science's Fusion Energy Sciences Advisory Committee (FESAC). I want to stress that today I am presenting my own opinions and not necessarily those of LLNL.

With my testimony, I hope to convey several points:

- Recent breakthrough results from National Ignition Facility (NIF) inertial confinement fusion (ICF) experiments have demonstrated capsule gain and burning plasmas; they have placed us on the threshold of fusion ignition where energy gain from nuclear fusion in the capsule exceeds the laser energy delivered.
- Achieving fusion ignition is the first major hurdle in efficiently harvesting fusion energy through inertial fusion energy (IFE), an innovative approach that is complementary to mainstream magnetic fusion energy (MFE) research. Currently, IFE is not part of the long-term energy R&D portfolio of the U.S. and is not part of the research being pursued at LLNL.
- The United States is the world leader in high energy density science which underpins the physics of fusion ignition, thanks to investments by the National Nuclear Security Administration (NNSA) and the DOE Office of Science. We are exploiting these extraordinary capabilities to perform world leading science and develop advanced technology. However, the U.S. lead is being challenged and competition is fierce.
- NIF's mission is scientific research of ICF to support the Stockpile Stewardship Program (SSP). It differs from what is needed for an IFE power plant. Developing IFE toward the goal of a clean energy source is a distinct challenge, yet one that is highly synergistic with NNSA's SSP mission under the ICF program.
- The time is right to restart an IFE program in the U.S. – decades of expertise in ICF which has brought us to the threshold of ignition combined with advances in our computing modeling capabilities and new emerging technologies such as novel laser architectures of relevance to IFE, machine learning, innovative diagnostics, and a growing community of skilled researchers can enable rapid progress.
- Through the recent 2020 FESAC Long Range Strategic Plan, the fusion community strongly endorsed the re-establishment of an IFE program.

The National Ignition Facility (NIF) Achieves the Threshold of Ignition

This past August, a breakthrough fusion experiment achieved a yield of 1.35 megajoules on the National Ignition Facility (NIF), more than two-thirds of the 1.9 megajoules of laser energy deposited on the target, and eight times more than the previous record (see Figure 1). This result places NIF on the threshold of fusion ignition for the first time, and demonstrates the feasibility of laboratory-scale laser driven inertial confinement fusion to achieve high-yield conditions.

The NIF is a football-stadium-sized facility that houses the world's largest, most energetic laser (approximately 60 times more energetic than any other laser in the world when it was completed in 2009). The precision and repeatability of this laser system are unprecedented in the world. NIF's 192 laser beams are guided and amplified through thousands of optical elements and then focused onto a miniature, highly engineered target the size of a BB. Inside this target is a spherical capsule containing the fusion fuel. The result is a hotspot the diameter of a human hair that creates conditions hotter and denser than those found at the center of the sun.

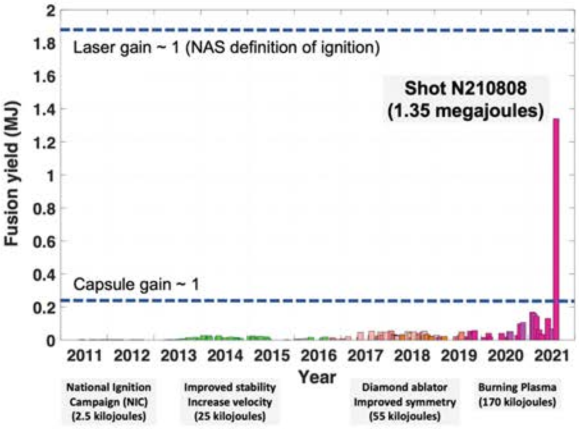

Figure 1. Shot N210808 on NIF produced more than 1.35 megajoules of fusion yield and marks a significant advance in ICF research. The histogram shows the progress over a decade of dedicated research and development on the NIF.

The central mission of the NIF is to provide experimental insight and data for the National Nuclear Security Administration (NNSA)'s science-based Stockpile Stewardship Program (SSP). Experiments in pursuit of fusion ignition are a vital part of this effort. They provide data in an important experimental regime that is extremely difficult to access, furthering our understanding of the fundamental processes of fusion ignition and burn, and enhancing the simulation tools that support our stockpile stewardship mission. Fusion ignition is the gateway toward even higher fusion yields in the future.

While full scientific interpretation of these latest results is still ongoing and will be vetted through the scientific peer-reviewed process, initial analysis shows that this experiment generated more than 10 quadrillion watts of fusion power for 100 trillionths of a second from a 50 micron-size burning plasma. This equates to an improvement of eight times over experiments conducted in the spring of 2021 and a 25-fold increase over the yield from a year ago. This shot also achieved capsule gain (defined as the ratio of energy released over the energy absorbed by the capsule) exceeding a factor of five. By the National Academy of Sciences 1997 definition of ignition (wherein the energy out of the target is equal to the total laser energy incident on it), the gain was 70% of that needed for ignition.

The experiment built on several advances gained from insights developed over the last few years by the NIF team, including new diagnostics; fabrication improvements in the target that include the hohlraum, capsule shell (which contains the deuterium and tritium fuel), and fill tube (by which the capsule is filled with the fusion fuel); improved laser precision; and design changes to increase the energy coupled to the implosion and the compression of the implosion.

These recent results now also open a vast new frontier for scientific exploration and exploitation. The same fusion plasmas that we create for ICF national security applications can also be exploited to become the basis of a future clean nuclear power source, which will also contribute to domestic energy independence and security.

Progress in Inertial Confinement Fusion (ICF) lays the groundwork for Inertial Fusion Energy (IFE)

As we approach inertial confinement fusion (ICF) ignition on the NIF, this will represent the first time in the laboratory that a fusion reaction will release more energy than was used to generate the reaction. This breakthrough forms the basis of a possible path to fusion energy that has significantly different technological and engineering risk portfolios than the concepts being pursued for magnetic fusion energy. To be clear, however, NNSA does not have an energy mission and, therefore, no NNSA resources are being used for inertial fusion energy (IFE) research at LLNL.

It must be acknowledged that, like all approaches to fusion energy, there are many scientific, technological, and engineering challenges to IFE. An IFE system would work by using a driver (such as a laser) to implode an injected target to fusion ignition and high energy gain conditions many times per second. Net electrical energy gain should be possible when the ratio of fusion energy released to input driver energy is on the order of 100 times the input energy. To make this possible, significant technological hurdles need to be overcome: ignition schemes with high yield and robust margin must be developed; drivers must be developed that have high efficiency and that can be operated at repetition rates of several times per second; ignition-quality targets must be economically mass produced, efficiently driven, and stably imploded that yield high gain at the rate of many times per second; optics and hardware produced that can withstand continual exposure to both high optical irradiance and fusion radiation; and reactor chambers must be designed to contain the micro-explosion products and adequately protect the driver. Furthermore, each of these systems will have to be engineered with cost, operability, and maintainability in mind required for economical energy production.

The National Academy of Sciences studied this problem and released an excellent report in 2013 entitled "An Assessment of the Prospects for Inertial Fusion Energy." A number of findings and conclusions were made, including one that "The potential benefits of energy from inertial confinement fusion (abundant fuel, minimal greenhouse gas emissions, and limited high-level radioactive waste requiring long-term disposal) also provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy. A portfolio strategy hedges against uncertainties in the future availability of alternatives such as those that arise from unforeseen circumstances." The report was also clear in concluding that "The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved."[1] This is the time to begin as we stand at the threshold of ignition.

Fusion energy research is a high-stakes endeavor, and as such, technological diversity is always a good strategy. NNSA has made a significant investment in ICF, NIF, and other ICF-relevant facilities such as the Z Pulse Power Facility at Sandia National Laboratories, and the Omega Laser Facility at the University of Rochester. The DOE Office of Science Fusion Energy Sciences program can and should leverage this to help establish the IFE path forward.

The U.S. is the world leader in high energy density science, although that lead is being challenged

The study of the extreme density, temperature, and pressure conditions like those found in ICF plasmas is called high energy density (HED) science. U.S. investments supported by NNSA and the DOE Office of Science have made the U.S. the world leader in this area of science, giving the U.S. a competitive advantage. As an example, when completed in 2009, NIF operated with 60 times more energy than the next biggest laser in the world, which was the Omega Laser Facility, also in the U.S. Now, nearly a decade later, NIF operates with 10 to 20 times the energy of the next most energetic laser, which is in China. There are few fields of science today where the U.S. has had, and currently maintains, such a large lead over the rest of the world. This lead exists not only in facility capabilities but also in diagnostics, targets, simulations, and scientific output and publications. This world leadership along with the compelling scientific opportunities – especially the grand challenge of inertial confinement fusion ignition and the potential of a path to inertial fusion energy – has been a magnet for the best and brightest scientists and engineers to pursue research in HED science and to work as part of the SSP.

The world leading nature of NNSA's ICF facilities requires cutting edge science and technology that in turn leads to many spinoff benefits. For example, NIF requires unique capabilities in lasers, optics, precision target fabrication, diagnostics, and computer controls. Developments in these areas have led to a large number of R&D 100 awards over the years and a proliferation of ideas that support our national security (e.g., directed energy weapons) and our economic competitiveness (e.g., extreme ultraviolet lithography, an approach to help extend Moore's law in chip making, is a spinoff of inertial confinement fusion laser research).

While historically we have had an impressive lead in HED science, it is clear today that the rest of the world is aggressively focusing on catching up. Currently, megajoule (NIF) scale lasers are under construction in both France and Russia. The Chinese have completed and are operating the second most energetic laser in the world and are publishing papers with designs for lasers 50% to three times the size of NIF. Having more energy makes achieving inertial confinement fusion ignition easier.

The area of high intensity lasers is a particularly noteworthy example. Researchers in the U.S. pioneered the field of high intensity lasers. These lasers reach more extreme conditions not by increasing the energy delivered, but by reducing the duration of the laser pulse, achieving higher and higher powers as the duration is reduced. In the 1990s, LLNL broke the petawatt (10^15 watts) barrier with the construction of the Nova Petawatt. A number of novel and important new

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[1] *An Assessment of the Prospects for Inertial Fusion Energy*, Committee on the Prospects for Inertial Confinement Fusion Energy Systems; NAS (National Academies Press, Washington, D.C., 2013).

properties emerged at the high intensities that these new lasers enabled, and since then dozens of petawatt class lasers have been built and thousands of publications about the exciting science in this area were published over the next 20 years. In 2017, the National Academy of Sciences published a report on "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light." A key conclusion from this report is that:

> "The U.S. has lost its previous dominance. The United States was the leading innovator and dominant user of high-intensity laser technology when it was developed in the 1990s, but Europe and Asia have now grown to dominate this sector through coordinated national and regional research and infrastructure programs. In Europe, this has stimulated the emergence of the Extreme Light Infrastructure (ELI) program. At present, 80 to 90 percent of the high-intensity laser systems are overseas, and all of the highest power (multi-petawatt) research lasers currently in construction or already built are overseas."[2]

The DOE Office of Science's Fusion Energy Science Program has since started to respond, and we applaud them for pushing forward the Matters at Extreme Conditions (MEC) Upgrade project at SLAC National Accelerator Laboratory's Linac Coherent Light Source (LCLS), which recently achieved Critical Decision 1 (CD1) in the project stage. This project will integrate state-of-the-art high-energy, high-repetition-rate lasers with SLAC's x-ray light source to provide an unprecedented HED science platform (see Figure 2). Leveraging these advanced laser systems and reaping the potential rewards for HED science, however, also requires commensurate investment and development in massively parallel target fabrication and characterization, target debris management and mitigation, electromagnetic pulse (EMP) and radiation hardened diagnostics, and real-time data management and analysis coupled to sophisticated simulation codes. These capabilities are crucial for enabling the next frontier in data-driven HED science and are also key to advancing IFE.

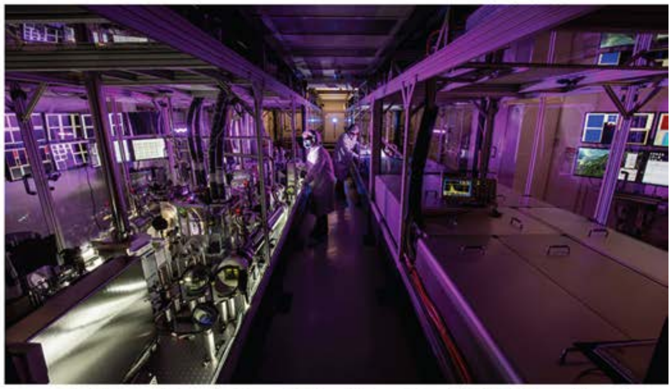

Figure 2. The High-repetition-rate Advanced Petawatt Laser System (HAPLS) is the world's most advanced, highest average power, diode-pumped laser system. It was designed, developed, and built by LLNL for the Extreme Light Infrastructure Beamlines (ELI-Beamlines) in the Czech Republic. A higher energy version is planned for the new MEC-Upgrade project at SLAC National Accelerator Laboratory, ensuring an unprecedented HED science capability for the U.S.

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[2] *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, Committee on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers; NAS (National Academies Press, Washington, D.C., 2017).

The synergies between IFE and ICF are many and mutually beneficial

The NIF is a marvel of science and engineering, allowing for research at the cutting edge of the most extreme conditions in the universe. However, it is exactly that – a scientific exploration facility, and very different from what would be needed for an inertial fusion energy power plant. As briefly touched on above, an electricity-producing IFE power plant would also require, for example, a more robust, high-yield ignition scheme likely different from what is pursued as part of the SSP; a driver, target injection, and tracking system, all operating at high repetition rates; an energy conversion system; robust first walls and blankets for wall protection, tritium processing and recovery, remote maintenance systems, and more.

The development of IFE towards the goal of a clean energy source, is distinct yet highly compatible with NNSA's SSP mission through the ICF program. The synergies between IFE and ICF are many and mutually beneficial; for example, advanced targets that could yield high gain for IFE could similarly produce high neutron yield for ICF applications, while improvements in driver cost and repetition rate for IFE could similarly mean more HED experiments for SSP. Furthermore, IFE offers a long-term solution for climate change and energy security – important factors in the overall national security landscape.

The exciting vision of IFE also serves as an important recruitment and training tool for many DOE missions. Generations of laser and plasma physicists, scientists and engineers, have been drawn to the field for the opportunity to be involved with the big science and challenging problem of fusion. The current U.S. leadership in HED/ICF research stems, in part, from the historical pursuit of IFE and as such, we must continue to take a leading role in IFE to maintain preeminence in this arena. The U.S. has an opportunity now to grow the national program by nourishing and leveraging our leadership in ICF with unique and world-leading competencies in the underlying science and technology that underpins IFE.

The time is right to restart an IFE program in the U.S.

The DOE is in an excellent position to make rapid progress in this area by leveraging the large investment being made in many emerging technologies and by the NNSA in ICF research. Many institutions already active in HED research would be well-positioned to contribute to this activity.

A number of promising technologies key to eventual IFE systems are making steady progress. In particular, exciting advances in repetition-rated high-energy laser technology and repetition-rated pulsed power technology in the U.S. over the last few years potentially lower the cost of a future driver for an IFE system. Additive manufacturing and other automated manufacturing techniques are becoming more cost-effective and are being used as part of the current target fabrication effort on NIF. Artificial intelligence and machine learning are being deployed to train large-scale, high-performance, high-speed models, improve predictive simulation models, and quantify uncertainties.

Many countries are ramping up efforts in IFE alongside magnetic fusion energy. EUROFusion, a consortium of nine European nations, is working on a Roadmap for an Inertial Fusion European Demonstration Reactor, and China and Russia are already building "NIF-like" lasers. The fusion energy industry is rapidly growing, already seeded by more than $2 billion of investment. The competition is substantial, but significant potential for productive partnerships and progress in fusion energy abound. For example, while public and private strategies differ in technical focus and deliverables, significant overlaps exist that are beneficial to both parties. Strategically partnering the public and private sectors can result in rapid enhancements in scientific and technological capabilities.

IFE is a multi-decadal endeavor and will require innovation to enable an economical energy source. This is an opportune time to move aggressively toward developing fusion energy as the world pushes toward decarbonization to mitigate the effects of climate change. Unlike other renewable energy sources, IFE would be both high-yield and extremely reliable, not susceptible to variables such as the weather or extended supply-chains. Future energy sources such as IFE will help make the nation more robust to potential geopolitical complications and alleviate our dependency on foreign energy providers.

The recent 2020 FESAC Long Range Strategic Plan endorsed the re-establishment of an IFE program

I had the honor of serving on the subcommittee that authored the 2020 FESAC Long Range Strategic Plan "Powering the Future: Fusion and Plasmas."[3] The report provides a decade-long vision for the field of fusion energy and plasma science and presents a path to a promising future of new scientific discoveries, industrial applications, and, ultimately, the delivery of fusion energy. The research community worked for more than a year to develop a wealth of creative ideas designed to accelerate fusion energy and advance plasma science, culminating in a consensus Community Planning Process Report. The FESAC report drew heavily on that report, to identify critical areas for research and development and prioritized investment.

Among the recommendations was to "strengthen the innovative and transformative research program elements that offer promising future opportunities for fusion energy commercialization: stellarators, liquid metal plasma-facing components, IFE, and alternate concepts... An IFE program that leverages U.S. leadership and current investments should be targeted."

Under the charge for the report, the committee was to determine a prioritization of projects and research programs under a number of different budget scenarios. Even at the constant level of effort budget scenario (flat funding relative to FY2019 budget levels), the committee recommended supporting a modest IFE program, focused on developing enabling technologies, through redirection of existing funds. The return on investment with even just modest funding for IFE is substantial, accelerating the fusion energy mission and providing excellent science, and aiding in the development of emerging technologies and innovative R&D. This underscores the community's commitment to the re-establishment of a robust IFE program in the U.S.

With the recent game-changing results on the National Ignition Facility bringing us to the threshold of ignition, and our decades of expertise in inertial confinement fusion science and technology, the U.S. is well-poised to make significant advances toward an inertial fusion energy future. IFE can enable a route towards clean and commercially viable power as well as unraveling mysteries of plasmas in our universe and developing technologies with broad societal impacts.

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[3] *Powering the Future: Fusion and Plasmas,* A Report of the Fusion Energy Sciences Advisory Committee, U.S. Department of Energy, Office of Science, Fusion Energy Sciences (2020)

Tammy Ma

Dr. Tammy Ma leads the High-Intensity Laser High-Energy-Density (HED) Science Element in the Advanced Photon Technologies (APT) Program within NIF and Photon Sciences at Lawrence Livermore National Laboratory (LLNL). This group pioneers use of the highest intensity lasers in the world to investigate novel states of matter, generate energetic beams of particles, study laboratory astrophysics, and explore fusion physics.

She currently also serves as the Deputy Director for LLNL's Laboratory Directed Research & Development (LDRD) Program.

Tammy earned her B.S. degree in Aerospace Engineering from Caltech in 2005, and her M.S. in 2008 and Ph.D. in 2010 both from the University of California, San Diego. Since joining LLNL, she has led many inertial confinement fusion experiments on the NIF, developed new x-ray diagnostics, and chaired the Lab-Wide LDRD program funding highly innovative research.

She has authored or co-authored over 185 refereed journal publications, and currently sits on the Fusion Energy Sciences Advisory Committee (FESAC), providing advice to the U.S. Department of Energy's Office of Science on complex scientific and technological issues related to fusion energy and plasma research.

Tammy was the recipient of the 2013 Presidential Early Career Award for Science and Engineering (PECASE), the 2016 Stix Award for Outstanding Early Career Contributions to Plasma Research from the American Physical Society for her work in quantifying hydrodynamic instability mix in ICF implosions, a 2018 DOE Early Career Research Award, and the 2021 Fusion Power Associates Excellence in Fusion Engineering Award. She was also named 2019 Woman of the Year for the California 16th Assembly District for her commitment to education, and to mentoring and encouraging young students who share her passion for science. She is a Fellow of the American Physical Society.

Chairman BOWMAN. Thank you, Dr. Ma.

Dr. Mumgaard, you are now recognized.

TESTIMONY OF DR. ROBERT MUMGAARD, CEO, COMMONWEALTH FUSION SYSTEMS

Dr. MUMGAARD. Chairman Bowman, Ranking Member Weber, and other distinguished Members of the Subcommittee, my name is Bob Mumgaard. I'm appearing before you today as the CEO of Commonwealth Fusion Systems. I'm also a board member of the Fusion Industry Association. I'd like to thank the Subcommittee for this opportunity to provide an update on the status and prospects of commercial fusion energy.

After years of study, we are now at the beginning of fusion's transition from a science to commercialization. Fortunately, we are building off of a strong base set by basic research funded by the government. Commercial fusion energy could be a gamechanger in the clean energy transition, and if fusion is to make an impact, it will necessarily create an entirely new industry of the scale of the semiconductor or aerospace industry with important companies like Boeing and Intel. The future of fusion industry will bring manufacturing, skilled jobs, and exports. And importantly, we get to decide how that industry will work. We can build in inclusion, diversity, equality at the outset of a technology that is inherently environmentally just.

Unfortunately, as I look across the U.S. publicly funded program, it's no longer clear that the United States has broad world leadership. Much of the program in the United States today looks the way it looked 10 years ago. We risk stagnation at the time the rest of the world has aggressively moved forward. The U.K., Germany, Japan, Italy, they are building facilities first conceived by the United States. China is rapidly investing. The U.K. has a governmentwide goal to be first and is already siting their first plant.

However, from where I sit I see three reasons why I'm very optimistic the United States can create a definitive lead in this new industry. First, the growth of the private sector. Over $2.4 billion in private capital has been invested in the fusion companies that now number nearly 30. This is a similar amount of capital as in nuclear fission small modular reactor companies. This is coming from a large range of investors across venture capitalists, to university endowments, to large energy companies. And they are putting capital at risk in fusion because they understand that the world needs a fundamentally new source of clean energy if we are going to meet our decarbonization goals. And these companies are highly ambitious with a recent survey stating that 84 percent of them believe that fusion will be on the grid in the 2030's or earlier. They are now building large facilities that over the next few years will be world-leading.

And CFS is an example of such a company. We have benefited from public investment in fusion science whether history or—at MIT. Our approach is based on the scientifically proven tokamaks, similar to the design to ITER. But in our case we've used new technology, new developed and successfully demonstrated high temperature superconducting magnets that allow us to shrink that tokamak to 1/40 the size of ITER. And CFS is currently building the machine, SPARC, at a site in Devens, Massachusetts. And based on peer-reviewed publications, we have high confidence that SPARC will be a net energy fusion machine and will achieve burning plasmas, which we aim to do in 2025, much earlier than people thought was possible. And after that we will proceed with the commercialization of our first fusion pilot plant called ARC. We hope to have that online in the early 2030's and are starting to engage customers who have interest. In fact, since the last House hearing on fusion, we have doubled six times over, and we will double again this year.

We will not wait to make decisions. We are executing. And we are not alone. The other companies like TAE and General Fusion, Helion Energy, Tokamak Energy are looking at similar timeframes and experiencing similar growth. All of these companies are looking to see which governments are going to be the best partners. And unfortunately, we are already seeing defections with a major facility that could have been built in the United States instead being built in the U.K. It would be much better if the U.S. public program leveraged the private sector, aligning with the technical goals and timelines, to keep it happening here.

The second reason I'm optimistic is that the public program has produced a consensus plan. Detailed in the National Academies and FESAC recommendations is a transition of the public-funded program toward the United States developing commercial energy. We need to stop some activities and transition to others, but the researchers are enthusiastic, and they are ready. We have a new generation of leaders at national laboratories and universities hungry to develop that technology. And that plan has been authorized but has not yet been implemented. In order to be a world leader, we need to implement that plan and increase its speed aggressively.

The third reason I'm hopeful is the movement toward public-private partnerships. And we know that when the public and private sectors work together and recognize what each side is good at, we create vibrant ecosystems. We saw this in commercial space with NASA (National Aeronautics and Space Administration) and SpaceX. We saw it even more recently with the COVID–19 vaccine. Working together, we can drastically reduce timelines to not just first-of-a-kind but large markets. And the recent *Energy Act of 2020* passed into law has just such a milestone-based program for fusion, and that needs to be implemented.

Commercial fusion energy is within our grasp as a viable source of clean energy led by the United States if we act now. I am very excited to have this panel and have this Committee take a look at this and open the discussion. Thank you.

[The prepared statement of Dr. Mumgaard follows:]

Written Testimony of Bob Mumgaard, Ph.D.
CEO, Commonwealth Fusion Systems

Subcommittee on Energy
Committee on Science, Space and Technology
United States House of Representatives

Fostering a New Era of Fusion Energy Research and Technology Development
November 17, 2021

Chairman Bowman, Ranking Member Weber, and other distinguished members of the Subcommittee, my name is Bob Mumgaard and I am appearing before the Subcommittee today as the CEO of Commonwealth Fusion Systems and as a Board Member of the Fusion Industry Association. I would like to thank the Subcommittee for this opportunity to provide an update on the status and prospects of commercial fusion energy.

I also want to thank the Committee for all its work and support on commercial fusion through its authorizing legislation in the *Energy Act of 2020*, the *Department of Energy Science for the Future Act,* and the *Build Back Better Act* bill currently moving through the Congress which would provide important funding to leverage the unique strengths of both the public and private sectors as we work to bring fusion energy to the grid.

Commercial fusion energy will be a game changer in the clean energy transition. It will provide zero-carbon, safe, and limitless power for the world. Most importantly, it is a solution that can be deployed at the scale of the problem that is climate change and at the speed required for the energy transition. The fusion community has been studying fusion science for decades, understanding its potential as an energy source. But we are at a unique moment in time with the advent of new commercial technologies and private investment of $2.4 billion flowing into a growing number of commercial fusion companies, all while countries around the world enact bold new programs. I am confident that with the right programs the feasibility of commercial fusion power plants will be demonstrated this decade, followed by commercial fusion power plants on the grid starting in the early 2030s

We are about to enter the era of commercial fusion energy, but there is a global race, and the U.S. is falling behind as other countries are working to progress pathways for a commercial fusion energy sector and outspend the U.S. on programs such as public-private partnerships, enabling technologies, appropriate regulation, and aggressive plans to be first in this energy source. Despite being a historical leader in fusion, the last 10 years have seen the U.S. cede leadership in the publicly funded program to other nations who were willing to enact bold new programs while the U.S. public program has largely stagnated. To regain a leadership position, the U.S. must increase resources and investments into fusion energy. This is done by leveraging the government investment in fusion research at National Laboratories and universities, while also developing new programs that align with developments happening in the private sector. The U.S. Department of Energy Fusion Energy Sciences program, the primary funder of fusion research, needs to act quickly on plans already developed to match the moment or else the U.S. will irrecoverably cede a fusion industry to other nations. Failing to act means that instead of selling commercial fusion power plants as a large globally important industry, the United States will be buying them from overseas.

We need only to look at the impressive track record of establishing new industry sectors such as space, biotech, and others to know that the U.S. can lead in bringing fusion energy to the world by combining the American entrepreneurial spirit, robust capital markets and full life cycle R&D investment of the private sector with the right support from the U.S. government.

Fusion's role in the global energy transition

We need deep decarbonization at a global scale that can support continued global economic growth and prosperity, while at the same time achieving the stated U.S. goal of a net-zero economy by no later than 2050.

Growth of the renewables sector in the past decade, specifically wind and solar has been strong enough that in 2019 more renewable energy was consumed than coal electricity in the U.S.[1] But strong continued growth of intermittent renewables alone cannot get us to net-zero emissions in a time frame that matters given renewables have been shown to have unfavorable cost scaling above 50% share.[23] We need a new dispatchable, zero-carbon electricity source that is scalable. To achieve zero-emissions electricity production by 2050 we will need one of the largest industrial transformations in history, with replacement plus expansion rates of ~100GW in new power plants. This is the largest problem and opportunity facing humanity and to solve it the market needs fundamentally new energy generation technology.

Fusion is that technology. Fusion is a zero-emissions dispatchable energy source that will be economically competitive and can scale-up rapidly.

Key attributes of commercial fusion energy:

- *Zero emissions:* no carbon dioxide, other greenhouse gases or pollutant emissions
- *Dispatchable:* can operate constantly and integrate with intermittent sources
- *Scalable:* freely available and inexhaustible fuel supply
- *Safety*: inherently safe with no meltdown or long-lived nuclear waste
- *Siting flexibility:* relatively small footprint and can be built anywhere
- *Robust Domestic Supply Chain:* built of mostly steel and concrete; manufacturable in the U.S. and would not require reimagining supply chains
- *Markets*: in addition to producing electricity, fusion is also a dispatchable source of high-quality heat that can unlock other hard-to-decarbonize markets e.g., hydrogen production, industrial process heat, green fuels, district heating, direct air capture of carbon dioxide, desalination, and others

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[1] https://www.eia.gov/todayinenergy/detail.php?id=43895

[2] https://www.iea.org/reports/net-zero-by-2050

[3] https://link.springer.com/article/10.1007/s10894-021-00306-4

- *Clean energy jobs*: replace existing energy production facilities and create clean energy, sustainable jobs for the future

The U.S. has an opportunity unlike any before to take a leadership role in fusion research and development by partnering with the private sector on the construction of the first major viable fusion energy demonstration and pilot plant facilities. To do so requires implementing a comprehensive plan.

There are numerous reports and experts closely examining how to accelerate putting fusion power on the grid. This includes the 2020 report "*Powering the Future: Fusion & Plasmas*"[4] from the Fusion Energy Sciences Advisory Committee that advised focusing on establishing the scientific and technical basis for a fusion pilot plant and the February 2021 National Academies' report "*Bringing Fusion to the U.S. Grid*"[5] which presented a strategic plan for a fusion pilot plant with the goal of producing electricity in the 2035-2040 timeframe. On October 19, 2021, the President's Council of Advisors on Science and Technology (PCAST) hosted a public discussion on "*The Potential for Integrating Fusion into the U.S. Energy Grid*"[6]. The U.S. Intelligence Community recognized the potential of the fusion private sector to address climate change in the *National Intelligence Estimate*.[7] The estimate suggests that a breakthrough in fusion via a startup company would alter the Intelligence Community's assessment of the likelihood of the world meeting the 1.5 degrees C goal. But capturing a first-mover advantage will require the U.S. Congress, the executive branch, the U.S. Nuclear Regulatory Commission (NRC), and state regulators to take concrete steps to enable a thriving domestic fusion energy industry.

If the U.S. does not act now, there is a risk that private companies will invest and construct their fusion power plants elsewhere in the world.

A growing fusion industry

U.S. government support for fusion research extends back to 1951 and has cumulatively totaled $32.5 billion[8]. The goals of the U.S. fusion program have been, broadly, to understand the scientific basis of fusion, and to pursue fusion as a viable energy source. However, in the U.S. the advent of the private fusion industry has always been understood to be an inevitable stage on the pathway to the widespread deployment of fusion power to the grid. It was not always clear when this private industry would appear, but it is now evident that the private industry ramp is underway.

According to a recent survey conducted by the Fusion Industry Association (FIA) and the UK Atomic Energy Agency (UKAEA)[9], there are now at least 35 global fusion companies and of those surveyed 52% were founded in the last 5 years alone. With increased capital now flowing into the private sector, we are seeing a shift that will lead to an acceleration of development in

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[4] https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf
[5] https://www.nap.edu/catalog/25991/bringing-fusion-to-the-us-grid
[6] https://www.whitehouse.gov/pcast/meetings/
[7] https://www.dni.gov/index.php/newsroom/reports-publications/reports-publications-2021/item/2253-national-intelligence-estimate-on-climate-change
[8] https://www.everycrsreport.com/files/20000131_RL30417_3fe121b74567d1e4bdb7c55100dd800ef5c67640.pdf
[9] https://www.fusionindustryassociation.org/about-fusion-industry

fusion energy technologies. By leveraging prior publicly funded work, private investments in fusion will enable more research and innovation at a much faster pace.

The report also indicated that of the 23 companies surveyed, of which 57% were U.S. companies, nearly $1.9 billion of private capital has been raised for commercial fusion energy, and this is now $2.4 billion with another funding announcement since the report was released a few weeks ago[10]. All indications are that this investment trajectory is likely to continue. The vast majority of fusion innovation is focused on electricity generation, and a majority (83%) of the companies that responded to the survey stated they believe the world will see fusion power on the grid in the 2030s or earlier.

It is recognized that the private sector builds on the previous successes of fusion energy achieved at laboratory scale around the world. Now scientists, investors, and business leaders are convinced that net gain (more energy output than input) from fusion is within reach. Private companies are exploring numerous approaches to achieving net energy fusion, including:

- *Magnetic Confinement Fusion*: Confining hot plasma fuel within a chamber with magnetism;
- *Inertial Confinement Fusion:* Compressing and heating the fuel so fast that fusion takes place prior to the central fuel interacting with surrounding materials; and
- *Magneto-inertial Confinement Fusion:* Combining aspects of magnetic and inertial confinement to contain the hydrogen plasma fuel.

This growth in the private sector demonstrates the need for a significant shift in the priorities of the government-funded public programs if they are to remain relevant and engaged in the deployment of fusion power plants. Public programs were previously responsible for every aspect of fusion device design, engineering, construction and operations. However, private industry progress frees them to focus on their core capabilities. Private fusion is proving its ability to execute large hardware projects, including integrated fusion device demonstrators, and enabling technologies such as high-field magnets, at speeds many times faster than possible in public programs. More importantly, the private sector will be engaging with end customers, bringing market relevance and the ability to speed up development of customer-driven solutions for fusion power systems.

This shift in roles in fusion energy development also brings new relevance to public-private partnership (PPP) initiatives. In 2019, the Department of Energy (DOE) launched the INFUSE program to connect private fusion enterprises with National Labs, supported by the Office of Science's Fusion Energy Sciences (FES) program. The program offers funding opportunities for projects with awards of $50,000 to $200,000 each and a 20 percent cost-share for private industry partners. The Advanced Research Projects Agency — Energy (ARPA-E) within the DOE has funded over $80 million in fusion research at both public and private organizations

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[10] https://www.helionenergy.com/articles/helion-raises-500m/

since 2015 and is currently executing another round of funding expected to support $29 million in programs through 2025.

We appreciate the U.S. government's support of the private fusion industry to date. However, current federal investment amounts are simply not sufficient for the U.S. to regain its global leadership position in fusion energy, nor to attract or meaningfully support commercial fusion companies capable of building a domestic fusion energy sector. The described ARPA-E programs are one-time, and the only annually recurring fusion public-private partnership program, INFUSE, is currently supported at just $4 million per year. By comparison, the private fusion industry is poised to construct over $2 billion of new integrated fusion demonstration facilities over the next couple of years. It is critical that PPP programs for fusion scale up to remain relevant with the planned private sector investments and accelerated timelines.

New private public partnerships to advance commercial fusion energy

A promising development for the fusion industry has been the milestone-based approach for a fusion cost-share program, as established by Congress through the Energy Act of 2020. Under this program industry would accept the bulk of the risk by funding its activities until milestone achievement, at which point the government would reimburse industry for its share of the costs (no more than 50%). This is a highly leveraged option for government investment in fusion with the private sector carrying the risk of schedule and cost overruns.

The cost-share program is modeled after the National Aeronautics and Space Administration (NASA) successful Commercial Orbital Transportation System (COTS) program, a program this Committee played a key role in establishing several years ago. The COTS program provided NASA with a 10x reduction in launch vehicle program costs, as well as a 2.5x reduction in management costs and has directly contributed to a thriving commercial space industry.

In May 2020, DOE issued a Request for Information to gather input on the fusion cost-share program about the topical areas, program objectives, eligibility requirements, program organization and structure, public and private roles and responsibilities, funding modalities, and assessment criteria of a cost share public-private partnership program. While the program has been authorized, no funds have been appropriated. Maintaining the funding for the cost-share program included in the text for the Build Back Better Act currently progressing through Congress will be critical for DOE to move forward on implementing the program. If the fusion cost-share program is successful it would lead to new privately constructed fusion facilities testing key aspects for commercial fusion energy and possibly one or more net-energy fusion systems deployed in the U.S. The time to put fusion energy on the grid would be reduced dramatically.

We are at an inflection point for fusion energy. The DOE's Fusion Energy Science program needs to act quickly on already developed plans and additions to existing and new programs that support private industry's accelerated timelines are critical. Additional opportunities could be identified through ongoing dialogue between the public and private sector, so we encourage the U.S. government to continue to explore how they can support the private sector and establish U.S. leadership in putting fusion energy on the grid in a time frame that matters for climate change.

Shift in fusion program emphasis

At the behest of Congress and DOE, the fusion community has laid out via a multi-year planning exercise the technology program that is required for the successful development of practical fusion power. This has been adopted by the FESAC panel as the recommendation to the FES program. This closely resembles the recommendations in two NAS panels. The key elements of this plan are a switch in mission from understanding plasmas to developing a fusion power industry, a switch in focus of the publicly funded program from plasma confinement physics to fusion technology development, and the construction of new facilities and test stands to solve the challenges of harnessing fusion power. This includes the construction of the fusion prototypical neutron source test stand, development of heat exhaust solutions, test stands for the tritium fuel cycle, and an increased emphasis on the material science for next generation fusion materials. Many of these programs are authorized in the Energy Act of 2020. If rapidly started and accelerated, this set of new programs would benefit the entire developing fusion industry.

Despite the comprehensiveness of this plan, direction from Congress, and authorization of programs, there are no current new programs in this space nor in their budget proposals. The time is now to rectify this. Such a change in direction would be a large but necessary change, particularly on aspects of interfacing with the private sector.

International governments competing for leadership in fusion energy

The U.S. is not alone in its pursuits and other nations are aggressively supporting development of fusion energy. Foreign governments are also making significant investments in public-private efforts to promote a domestic fusion industry. The United Kingdom has committed over a half billion dollars to fusion PPPs.[11] China is spending hundreds of millions per year[12] on their private fusion industry. This compares to $6 million for the DOE's INFUSE public-private partnership program proposed in the FY2022 budget.

The United Kingdom and China are targeting having a fusion pilot plant operational by the late 2030s and have kicked off a search for the site of that facility, while at present the U.S. programs are considering longer timelines culminating in a pilot plant in the 2040s. If the U.S. wishes to take an international leadership role in fusion, then it needs to accelerate the timeline for a fusion pilot plant to be ahead of its peers. The U.S. could accomplish this by aligning with and supporting the private fusion industry's goals to have a fusion pilot plant operational by the early 2030s.

In addition, the United Kingdom is leading in the development of a regulatory framework for commercial fusion that recognizes the significantly lower risk profile that fusion presents compared to fission. The United Kingdom government has indicated that future fusion energy facilities will be regulated in a similar manner to the Joint European Torus facility, rather than by agencies which oversee fission systems. From a risk perspective, fusion energy facilities are

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[11] https://www.neimagazine.com/features/featurefusion-projects-make-progress-in-2020-8492724/

[12] https://www.fusionindustryassociation.org/post/chinese-fusion-energy-programs-are-a-growing-competitor-in-the-global-race-to-fusion-power

much more like accelerator facilities that one would find in a hospital, and it makes sense to regulate them in a similar manner rather than impose the more onerous and wholly inapplicable requirements developed for fission technologies. These forward-looking regulatory strategies make the United Kingdom an attractive place for nascent fusion companies.

Furthermore, the United Kingdom has continued to build new facilities to test the components needed for a fusion power plant. These include facilities to develop the fuel cycle for fusion, to practice maintenance on a fusion power plant, to extract the heat from the fusion components, and to test materials. This technology focus will raise the readiness of all of the fusion entities working, both public and private entities. The U.S. has no such set of test stands or development programs despite the long-identified need for these facilities. Over the last five years, the United Kingdom has built in steel and concrete while the U.S. program has yet to implement the recommendations from expert reports.

Commonwealth Fusion Systems strategy for a fast path to fusion energy

Commonwealth Fusion Systems (CFS) is among the many start-ups we have seen emerge and joined the private sector over the past 5 years. In 2018, CFS was spun out of Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center after DOE's cuts to funding for MIT's long-standing fusion program. At that same time, new high temperature superconductors were becoming commercially available. The MIT team that would become CFS co-founders were exploring how this new material could be used to build a novel design for magnets that would be the strongest fusion magnets of its kind in the world. Magnets are the key technology in a fusion machine called a tokamak, the most widely studied machine for the magnetic confinement fusion described above. If we were able to build high-temperature superconducting (HTS) magnets, we knew that we could build smaller, faster, and less expensive fusion devices that would achieve net energy. It meant that we could provide economical fusion power, supplying humanity with abundant clean energy

CFS set out on an aggressive timeline for bringing fusion power to the grid. As a first step, with the backing of private capital and attracting top talent, the company and its collaborators at MIT delivered on its commitment to build and successfully test a first-of-a-kind high-field large-bore HTS magnet in September 2021. It is the largest HTS magnet in the world with a magnetic field of 20 tesla. The HTS magnet will allow for smaller devices than previous magnet technology. It will allow for SPARC, a tokamak device that will be 1/40th the size of the International Thermonuclear Experimental Reactor (ITER). SPARC is an important step to accelerate the development of commercial fusion energy. The compact configuration enables the team to rapidly incorporate innovations and provide time sensitive answers to questions surrounding both fusion science and technology.

CFS is currently building SPARC in Devens, Massachusetts (*Figure 1*), a device that will achieve commercially relevant net energy from fusion for the first time in history. The plasma physics for SPARC was validated in a series of seven peer-reviewed papers published in the Journal of Plasma Physics[13]. The papers show, point-by-point, using the absolute best simulations, physics, and tools, that if SPARC is built according to its design, it will work and

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[13] https://www.cambridge.org/core/journals/journal-of-plasma-physics/collections/status-of-the-sparc-physics-basis

Figure 1: Commonwealth Fusion Systems construction site in Devens, MA (11/09/21)

achieve a net energy gain of Q>10[14]. Gains of that level would serve as the basis for the design of an economical fusion power plant.

The SPARC facility is aimed at the same basic physics questions of the ITER facility and uses the same scientific and technology advances that underpin ITER. However, the reduction in scale afforded by the HTS magnets means that it can be constructed in a fraction of the time. This puts a burning plasma -- a long sought scientific goal-- in a much-accelerated time frame. SPARC is expected to become operational in 2025 and reach net energy fusion in the following year with burning plasmas soon after that. This timeline is nearly a decade faster to the scientific goals as ITER at less than 1/10th of the cost. This is the power of innovation and commercialization. This is a domestic facility, built by a U.S. entity, backed by private capital, creating a leadership opportunity for U.S. science, engineering, and industry creation.

This will require a meaningful and systematic collaboration between CFS and DOE that does not currently exist. This type of facility requires large scale programs, such as a milestone-based cost share program with U.S. publicly funded scientists obtaining burning plasma data earlier.

Following the SPARC demonstration in 2025, CFS plans to construct the world's first fusion power plant, ARC, and put electricity on the grid in the early 2030s. This will further demonstrate the science and technology required for economically competitive, mass production of fusion energy. It will pave the way for fusion systems that will provide carbon-free, safe, virtually limitless power for the world. However, the current publicly funded program's roadmap for developing the required technologies is not at the scale, timeline, or technology choices the private sector requires, thus companies could be forced to duplicatively develop technologies themselves.

At CFS, we are building a company with the know-how and capabilities to achieve these timelines. We also recognize the value in continued collaboration with national laboratories and universities for science research that can support and accelerate development in the fusion private sector. We look forward to growing existing and developing new public sector partnerships that put the U.S. on the fastest path to fusion energy on the grid.

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[14] Q = (fusion power out) / (Heating power in); net energy

Summary of recommendations to secure U.S. leadership in fusion energy

Expanded support for fusion energy programs is necessary to keep the center of the private fusion industry based in the U.S.

- The private sector is driving towards commercial fusion in the 2030s. Now is the time to make the necessary changes to align the public resources and funding to drive innovation and leadership in fusion energy. If the U.S. does not scale the public sector efforts and align them with the private sector, it may fall behind and miss the opportunity to be a leader in a large-scale energy transition to fusion power.

- Congress and DOE should quickly move to fully fund and implement the milestone-based fusion cost-share development program and support the funding for it and other fusion programs within the Build Back Better Act currently moving through Congress to ensure the first fusion power plant is built in the U.S, and at the same time continue to identify additional opportunities to enable a thriving private sector capable of rapid deployment of fusion power systems.

- Specifically, Congress and DOE should quickly move to implement the recommendations made in the recent National Academies and FESAC long range planning reports. These recommendations require that DOE pivot and be aligned with energy development for a commercial fusion pilot plant. These plans should be implemented in due haste and accelerated as much as possible as the window where they could create U.S. leadership and help the emerging private industry is quickly closing.

Thank you for the opportunity to share my views on the future of the private fusion industry in the U.S. Both Commonwealth Fusion Systems and the other members of the Fusion Industry Association look forward to the opportunity to continue to work with the committee to bring fusion energy to the grid in a time frame that matters for climate change.

Commonwealth Fusion Systems

Bob Mumgaard, Co-Founder and CEO

As the CEO of Commonwealth Fusion Systems (CFS) Bob Mumgaard is responsible for the strategic vision and direction of the company, paving the way for a future of clean unlimited fusion energy. Since co-founding CFS with a mission to commercialize the high-field approach to fusion, Mumgaard has grown the company to over 150 employees and raised over $250 million from some of the world's leading investors. CFS is a private commercial fusion company with a scientifically-validated path to commercialization.

Mumgaard performed his PhD work at MIT and during that time he contributed to the design of several small superconducting tokamaks for a variety of physics missions using high temperature superconductors (HTS). Prior to co-founding CFS, as an MIT fellow Mumgaard focused on how entrepreneurship, risk-retirement strategies, and partnerships could increase the speed of fusion from laboratory to market. He organized and led a team identifying strategies to utilize private finance and traditional academic resources to speed the path to fusion energy resulting in a collaboration model with MIT.

Mumgaard holds a PhD in Applied Plasma Physics and a MS in Nuclear Engineering from MIT, and a BS in Mechanical Engineering and BS in Engineering Physics from the University of Nebraska.

Chairman BOWMAN. Thank you, Dr. Mumgaard.

Dr. McCarthy, you are now recognized.

TESTIMONY OF DR. KATHRYN McCARTHY, DIRECTOR, U.S. ITER PROJECT OFFICE

Dr. McCARTHY. Thank you very much. Chairman Bowman and Chairwoman Johnson, Ranking Member Weber and Ranking Member Lucas, and Members of the Committee, thank you for this opportunity to discuss fusion energy. My name is Kathy McCarthy. I'm the Associate Laboratory Director for Fusion and Fission Energy and Science at Oak Ridge National Laboratory and Director of the U.S. ITER project.

The world is facing an urgent climate and energy crisis. Here in the United States we need a multipronged approach to meet our climate and energy goals. Today's nuclear energy from fission reactors provides abundant baseload carbon-free energy. Sustaining our current fleet is key to bridging to the near-term option, which is advanced nuclear reactors. Both current and advanced nuclear reactors are supported by the recently passed infrastructure bill, and ORNL is proud to play key roles in each.

But nuclear fusion is still the Holy Grail for energy. Fusion has the potential to provide abundant, safe, carbon-free energy for thousands of years and beyond. The path to fusion energy has benefited from a number of recent advances, including expanded scientific understanding of fusion plasma is key to preparing for ITER operations. ITER tokamak assembly and overall progress, the United States has already delivered the first two modules for the heart of ITER, the central solenoid magnet. Exciting results from the National Ignition Facility at Lawrence Livermore National Laboratory, accelerated understanding of plasma performance thanks to high-performance computing, and progress in the fusion industry with signs of successful leveraging of national laboratory expertise. It's important to have multiple paths to fusion under development given how challenging it is. Having multiple approaches reduces risk. Our investment in ITER remains vital to U.S. fusion goals.

The recent National Academies of Science, Engineering, and Medicine report, "Bringing Fusion to the U.S. Grid," states that, "Technology and research results for U.S. investments in ITER, coupled with a strong foundation of research funded by the Department of Energy, positioned the United States to begin planning for its first fusion pilot plant. Much of the experience gained through the ITER process is relevant to a pilot plant regardless of its configuration."

Already the challenge of designing, fabricating, delivering, and assembling first-of-a-kind components into the ITER tokamak is yielding practical fusion reactor experience. Domestic supply chains are being developed, fabrication challenges are being resolved, and integration issues are being addressed, all to assemble the world's first nuclear-certified fusion reactor.

In addition, the U.S. work force and fusion leadership is being maintained and further developed. For about 9 percent toward construction costs and 13 percent toward operation costs, the United

States receives 100 percent of ITER's science, technology, and associated intellectual property.

Recent reports from the scientific and engineering community have shown that the United States is now ready to add significant attention to fusion technology to develop a practical path to a fusion pilot plant. I was a member of the National Academies Committee that authored the report on "Bringing Fusion to the U.S. Grid." Our report emphasizes the need for investment in several areas to put the United States on a competitive path for a future fusion energy industry. Our final report states that, "Successful operation of a pilot plant in the 2025 to 2040 timeframe requires urgent investments by DOE and private industry. Both resolve the remaining technical and scientific issues and to design, construct, and commission a pilot plant.

In addition to what we gain from ITER, a path to a pilot plant demands operations of facilities such as the DIII-D tokamak at General Atomics in California and the Material Plasma Exposure eXperiment, MPEX, now under construction at Oak Ridge National Laboratory. Additional technology testing facilities and innovations are needed, as outlined in the report, such as a prototypic neutron source for testing of advanced structural and functional materials; integrated first wall and blanket testing to advance fuel producing technology readiness; and innovations in boundary plasma science, fueling technologies, and gas processing. All of these efforts will help fusion reach commercial viability.

U.S. ITER, Oak Ridge, and many of our other national laboratories are making crucial contributions to advance fusion science and technology and are engaged with industry to solve these challenges. These efforts, with an increased focus on technology, position our Nation to include nuclear fusion in our long-term carbon-free energy portfolio.

Thank you for your interest and your time today. I welcome any questions that you may have.

[The prepared statement of Dr. McCarthy follows:]

Statement of Kathryn A. McCarthy
Associate Laboratory Director for Fusion and Fission Energy and Science
US ITER Project Director
Oak Ridge National Laboratory

Before the Subcommittee on Energy, House Committee on Science, Space and Technology
U.S. House of Representatives

November 17, 2021

Hearing on Fostering a New Era of Fusion
Energy Research and Technology Development

Chairperson Bowman, Ranking Member Weber and Members of the Committee, thank you for this opportunity to discuss fusion energy. I am Dr. Kathy McCarthy, Associate Laboratory Director for Fusion and Fission Energy and Science at Oak Ridge National Laboratory and Director of the US ITER Project. I am a nuclear engineer and National Academy of Engineering member with over 30 years of experience in the fields of fusion and fission nuclear science and engineering. My career has spanned international fusion and fission research, U.S. Department of Energy National Laboratories at Idaho and now Oak Ridge, and the Canadian Nuclear Laboratories. I am pleased to participate in today's hearing with this distinguished panel today.

Oak Ridge National Laboratory is the largest U.S. Department of Energy (DOE) science and energy laboratory, conducting basic and applied research to deliver transformative solutions to compelling problems in energy and security. ORNL's diverse capabilities span a broad range of scientific and engineering disciplines, including nuclear fission and fusion. In fact, our history with fission and fusion is deep: Oak Ridge is the home of the first nuclear reactor to deliver electricity: the Graphite Reactor in 1948. We also have more than 50 years of experience in nuclear fusion. Our science and technology breakthroughs drive innovation today across government and industrial sectors.

ORNL benefits from the leadership of the Department of Energy through the Office of Science, the nation's largest supporter of basic research. We also support the Department of Energy's applied research programs, including the Office of Energy Efficiency and Renewable Energy, the Office of Nuclear Energy, and many other programs managed by DOE. For the hearing today, I want to especially point out the support of Fusion Energy Sciences in the Office of Science. Fusion Energy Sciences leadership understands the value of basic plasma science combined with fusion science and technology development. This is a necessary approach for advancing from the science of plasmas to practical fusion energy.

As the Associate Laboratory Director for Fusion and Fission Energy and Science, I am privileged to lead a talented group of scientists and engineers as we address scientific and technological challenges in both fission and fusion. Our nuclear research and development efforts span near-term technology deployments to the current commercial nuclear reactor fleet, advanced fuels and technologies such as advanced manufacturing supporting the deployment of next generation fission reactors, and the science of burning plasmas alongside the technology development to bring a fusion pilot plant to life. I also lead the US ITER project. US ITER is a multi-lab effort funded by the Department of Energy's Office of Science and managed by ORNL with partner laboratories Princeton Plasma Physics Laboratory and Savannah River National Laboratory to deliver US contribution to the international ITER project.

The Value of Nuclear Fusion

The world is facing a climate and energy crisis unlike any in human history. Here in the US, where the primary consideration is mitigating climate change, we need a multi-pronged approach to meet our climate and energy goals. As we shift towards greater electrification, our demand for carbon-free electricity will increase. Renewables play an important role in our clean energy portfolio, but their intermittent nature imposes limitations. Carbon-free, stable, reliable baseload is necessary, and nuclear energy meets those needs. Carbon-free baseload energy is also essential to expanding penetration of renewable sources such as solar and wind.

To address multiple challenges in the face of climate change, new forms of carbon-free energy must be part of our long-term energy planning. We need carbon-free energy now, but we also must make long-term plans for expanding our portfolio of baseload climate-friendly energy options.

Today's nuclear energy, from fission reactors, provides abundant base-load carbon-free energy. In the US alone, nuclear energy provides over half of our emission-free generation and about 20% of total electricity, all while producing at a greater than 90% capacity factor. Sustaining our current fleet now is key to bridging to the near-term option, advanced nuclear reactors. Advanced reactors have the potential to operate with improved efficiency, economy, and more diverse applications. Support of fission nuclear energy is critical for immediate and near-term delivery of carbon-free energy. Both current and advanced nuclear reactors are supported by the recently passed Infrastructure Bill, and ORNL is proud to play key roles in each.

However, nuclear fusion is still the holy grail. That is a commonplace perspective in our field because we think in terms of atomic reactions and their potentials. We *want* nuclear energy to evolve from our current designs. We in the field are deeply familiar with the power of nuclear energy compared to chemical reactions; moreover, we understand the challenge of managing fission power plants over time. The likely trajectory of nuclear power is towards advanced fission reactors and ultimately to fusion reactors.

The parallel development of fusion nuclear energy will lead us to a natural progression beyond today's reactors and near-term advanced reactors. Like other leaders in my field, I see current nuclear energy, advanced reactors, and fusion as allies. From that perspective, we seek to further develop carbon-free, baseload power via nuclear reactions. Ultimately, we believe that progress will lead to an emphasis on nuclear energy; and, ultimately, we expect a gradual transition from fission alone to a future with fusion. Why? When you're seeking to make both a near-term and long-term impact on energy emissions, nuclear energy is the best solution for power delivery, climate, and safety.

While delivering nuclear energy from fusion is a longer-term endeavor, it is worth the investment for our nation and indeed the globe. Fusion energy is the same process that powers our Sun and the stars. Fusion has the potential to provide enormous amounts of safe, carbon-free energy to the planet for thousands of years and beyond. Fusion fuels, isotopes of hydrogen, are abundant and can be produced from fusion reactions in a closed cycle. Long-term waste is easily managed, as the byproducts of a fusion reaction are helium and energetic neutrons. Fusion reactors could be productive, non-proliferative sources of clean energy and support equitable global access to reliable electricity.

Perspective on Fusion Achievements

The path to fusion energy has benefitted from several recent advances.

US investment in plasma science has yielded expanded understanding of fusion plasmas. This is critical for the nation to benefit from the international ITER project, which will demonstrate an industrial scale 500 MW "burning," or self-heated, plasma. The ITER tokamak uses magnetic confinement of plasmas; this approach has a large experience base including proven results at demonstrating fusion power.

The start of ITER tokamak assembly in 2020 and continued project progress shows us that it is possible to achieve engineering precision, at the millimeter-scale, on ship-sized fusion reactor components. ITER accomplishments are being realized under a long-term international agreement that benefits all partners, including the United States. Examples include tools and strategies for plasma heating, fueling and control, superconducting magnetic technologies, fuel cycle technologies, and fusion materials.

In addition to ITER, we are working on several other important projects that will help us develop the science and technology to make fusion a reality. For example, the DIII-D National Fusion Facility, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory and other labs and universities continue to make strides towards readiness for high power fusion performance. At these institutions we are learning how to manage and influence high power plasmas, and this will make a difference for ITER and for other fusion power endeavors.

Recent results from the National Ignition Facility at Lawrence Livermore National Laboratory have excited fusion experts about the inertial confinement approach to fusion. I defer to my colleague Tammy Ma to tell you more about this achievement. It is important to have multiple paths to fusion under development as it is a challenging technology, and pursuing multiple approaches reduces risk.

The application of supercomputing to modelling of fusion plasmas and devices has also accelerated understanding of the impacts of device designs on plasma performance. When we can extrapolate from one device to a new design, we can avoid building every device in between major steps. Oak Ridge National Laboratory and Princeton Plasma Physics Laboratory have advanced fusion modeling, leveraging their capabilities as national laboratories in this area. The Exascale Computing Project (ECP), managed by ORNL for the Office of Science, is developing building blocks such as fusion materials and fusion plasma performance, towards the whole-device modeling capability that will be needed. These applications also provide important insights into where fusion technology research and development should focus. Similarly, advances in plasma diagnostics have delivered high fidelity data from current fusion devices that aid extrapolation to future fusion devices.

In cooperation with the laboratories, the fusion industry is continuing to make progress, too. Investment in private fusion efforts continues to grow. The Department of Energy's Office of Science support for these endeavors, through programs such as INFUSE (Innovation Network for Fusion Energy, https://infuse.ornl.gov/) managed by Oak Ridge National Laboratory and Princeton Plasma Physics Laboratory is a great example of industry leveraging DOE laboratory fusion expertise. So far through INFUSE, 16 private companies are engaged in 40 projects with DOE laboratories to advance the technological readiness of components and systems for their novel fusion devices.

The Value of ITER Engagement

Our investment in ITER remains vital to U.S. fusion goals.

The international ITER project is the largest scientific collaboration underway in the world and is now under assembly in Saint-Paul-lès-Durance, France. The ITER mission is to demonstrate the scientific and technological feasibility of fusion energy by achieving a reactor-scale 500 MW self-heated or burning plasma. Production and control of a burning plasma is considered an essential step for practical fusion energy development. A burning plasma will demonstrate fusion reactions dominated by self-heating. The fusion reaction of hydrogen fuels will yield alpha particles that will sustain plasma heating and additional fusion reactions. To date, experiments to demonstrate fusion power have relied on external heating only.

For a path to practical, or deployable fusion energy—not just fusion science—U.S. fusion leaders emphasize that it is essential to master both the science and the technology required for producing and controlling a reactor-scale burning plasma. ITER offers that opportunity, plus access to all ITER intellectual property and the one-of-a-kind scientific facility for research on high power plasmas. For a ~9 percent contribution to construction and a ~13 percent contribution to operations, the United States receives 100 percent of ITER science, technology and associated intellectual property output, plus the opportunity to propose and direct science experiments at ITER.

Already, the challenge of designing, fabricating, delivering, and assembling first-of-a-kind components for the ITER tokamak is yielding practical fusion reactor experience that is invaluable for a path to fusion energy. Supply chains are being developed, fabrication challenges are being resolved, and integration issues are being addressed, all to assemble the world's first nuclear-certified (under French law) fusion reactor.

Most US ITER funding is for design, fabrication, and delivery of hardware components, and most of that funding remains in the United States. So far, over $1.3 billion has been awarded to U.S. industry, universities, or obligated to DOE National Laboratories to support R&D, design, fabrication, and delivery of US ITER scope. This funding not only contributes to state and regional economies, but also enables U.S. industry, universities, and laboratories to remain at the forefront of fusion technology and engineering. This effort is building a domestic supply chain for fusion technologies and components that can be marketed to the world. Additionally, and essential to US fusion leadership, this funding is developing and sustaining current and future fusion energy leaders.

U.S. participation in ITER was authorized by the Energy Policy Act of 2005. In 2006, the United States signed the Agreement on the Establishment of the ITER Fusion Energy Organization for the Joint Implementation of the ITER Project, a Congressional-executive international agreement, along with partners Japan, the European Union (project host), the Republic of India, the People's Republic of China, the Republic of Korea, and the Russian Federation.

These conclusions above and the importance of ITER is supported in multiple reports from the National Academies of Science, Engineering and Medicine (NASEM) (2019, 2021) and in the recently published DOE Fusion Energy Sciences Advisory Committee long-range plan for fusion energy and plasma science (2021).

The NASEM final report on a *Strategic Plan for Burning Plasma Research (2019)* notes "the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant."

The more recent NASEM report *Bringing Fusion to the US Grid* (2021) states that "technology and research results from U.S. investments in ITER, coupled with a strong foundation of research funded by the Department of Energy (DOE), position the United States to begin planning for its first fusion pilot plant.... While a pilot plant will differ considerably from ITER, and may not even be a tokamak configuration, much of the experience gained through the ITER process is relevant to a pilot plant regardless of its configuration."

U.S. is Ready to Prepare for a Fusion Pilot Plant

For much of the last 25 years, U.S. policy guided fusion research toward fusion science and the understanding of plasmas. Other nations across the globe, in contrast, have pursued the development of fusion energy alongside their science efforts. Examples include the European Demonstration Fusion Power Reactor (DEMO) design activities, the China Fusion Engineering Test Reactor, and other DEMO activities in Japan and South Korea. For the United States to remain a leader in key fusion areas and to be ready for the nuclear evolution that adds fusion to our carbon-free energy portfolio, we must invest in science, R&D and technology solutions to remove barriers blocking the path to fusion energy.

The FESAC long-range strategic plan (2021) released earlier this year and discussed in this hearing by my colleague Troy Carter, identifies priorities for investments. This plan was based on community input and has the support of the U.S. fusion community broadly.

To summarize the path to fusion, there are three main technology challenges that must be resolved for practical fusion energy:

- Creating and sustaining a fusion power source, namely a self-heated "burning" plasma
- Developing the materials that can survive extreme fusion environments for extended periods of operation; and
- Closing the fusion fuel cycle, including producing fusion fuel.

ITER will create and sustain a self-heated plasma at power plant scale. The other two areas—materials and fuel cycle—are less developed. In addition to our essential work on ITER, these two areas will require intensified efforts to achieve practical fusion energy on a competitive time scale.

Because of technical progress in the U.S. fusion program and through actions of the science community and industry, the aspirations and direction of U.S. fusion efforts have shifted to include an emphasis on a viable path to a fusion pilot plant and ultimately to the development of fusion as an energy source. Recent US reports from the scientific and engineering community have shown that the U.S. effort in fusion is now ready to add significant attention to fusion technology, to develop a practical path to a pilot fusion plant by the 2035-2050 timeframe, and ultimately to support a path to practical fusion energy before mid-century.

- The National Academy of Sciences, Engineering and Medicine (NASEM) report titled *Grand Challenges for Engineering* (2017) identified "Provide energy from fusion" as a grand challenge for the twenty-first century.

- The NASEM report titled *Burning Plasma Research* (2018) states that, "Now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take steps towards the development of fusion electricity for the nation's future energy needs."

- The American Physical Society Division of Plasma Physics community consensus report titled *A Community Plan for Fusion Energy and Discovery Sciences* (2020) noted that "fusion science and technology" is a crucial area for realizing the promise of fusion energy, along with plasma science.

- The Fusion Energy Sciences Advisory Committee report *Powering the Future: Fusion and Plasmas* (2021) represents a community-endorsed 10-year strategy for advancing both fusion energy and plasma science. In a major shift, this report places as much emphasis on fusion technology as on plasma science. The report states "now is the time to move aggressively toward the deployment of fusion energy."

- The NASEM report titled *Bringing Fusion to the US Grid* (2021) states "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," and further "Successful operation of a pilot plant in the 2035–2040 time frame requires urgent investments by DOE and private industry—both to resolve the remaining technical and scientific issues and to design, construct, and commission a pilot plant."

I was a member of the National Academy for Sciences and Engineering Committee on Bringing Fusion to the U.S. Grid. Our report emphasizes the need for urgent investment in several areas to put the U.S. on a competitive path for a future fusion energy industry that serves the nation and the world. Like the recent reports that preceded this report, our report recommends an expanded emphasis that encompasses fusion technology. In addition to the information from ITER construction and operations, operations of facilities such as DIII-D, and operation of the Material Plasma Exposure eXperiment (MPEX - currently under construction at ORNL) to name a few, the report identifies specific technology areas that need urgent investment. Examples include:

- A limited volume prototypic neutron source for testing of advanced structural and functional materials
- Integrated first wall and breeding blanket testing to advance blanket technology readiness
- Innovations in boundary plasma science, fueling technologies, and gas processing

This information is key not only for technical performance of a fusion pilot plant, but for evaluating economic attractiveness as well.

The report emphasizes the need for "the creation of national teams, including public-private partnerships, that will develop conceptual pilot plant designs and technology roadmaps that will lead to an engineering design of a pilot plant that will bring fusion to commercial viability." The report further stresses that these national teams should be diverse, with participants from industry, universities, and national laboratories. Each of these groups brings an important perspective that is necessary to identifying and solving the remaining challenges.

This clear emphasis on fusion technology is timely. Investment in fusion technology is essential to develop economically attractive fusion energy. The extreme environment of a fusion device requires materials that can perform reliably to minimize downtime, with a sustainable fuel cycle that uses fusion power efficiently. Our national laboratories, including Oak Ridge, are making crucial contributions, and are engaged with industry to solve these challenges and accelerate the path to practical fusion energy.

Thank you for your interest and this opportunity to share my thoughts with the subcommittee. I request that my written testimony be made a part of the public record, and I welcome any questions you may have at this time.

Kathryn A. McCarthy, Ph.D.

US ITER Project Director
and Associate Laboratory Director for Fusion and Fission Energy and Science
at Oak Ridge National Laboratory

Kathy McCarthy, Associate Laboratory Director for the Fusion and Fission Energy and Science Directorate, joined the Oak Ridge National Laboratory (ORNL) after three years as Vice President for Science and Technology and Laboratory Director for the Canadian Nuclear Laboratories, where she oversaw a staff of 650 and grew the labs' commercial work. She previously held a variety of engineering and leadership roles at Idaho National Laboratory (INL), including Director of Domestic Programs in INL's Nuclear Science and Technology Directorate, Director of the Light Water Reactor Sustainability Program Technical Integration Office, and National Technical Director for the Systems Analysis Campaign for DOE Office of Nuclear Energy's Fuel Cycle R&D Program.

McCarthy began her career in fusion technology with a focus on liquid metal blanket designs. She was a participant in the US DOE US-USSR Young Scientist program, which included experience at the Efremov Institute in Leningrad, Russia, the Latvian Academy of Sciences in Riga, Latvia, and the Kurchatov Institute in Moscow, Russia, and was also a Guest Scientist at the Karlsruhe Institute of Technology in Karlsruhe, West Germany.

McCarthy earned her Ph.D. in nuclear engineering from the University of California, Los Angeles, with a major field of fusion engineering and minor fields of nuclear science and engineering and physics. She was inducted into the National Academy of Engineering in 2019 and has received two American Nuclear Society (ANS) presidential citations and her awards include the 1996 ITER US Home Team Leadership Award, and the 1994 David Rose Award for Excellence in Fusion Engineering. McCarthy served on the Fusion Energy Sciences Advisory Committee from 1999 to 2013 and on the US ITER Technical Advisory Committee from 2010 to 2013 and has held numerous ANS leadership positions. She was elected as a fellow of the American Nuclear Society in 2021.

Chairman BOWMAN. Thank you, Dr. McCarthy.

At this time we will begin our first round of questions. I now recognize myself for 5 minutes.

Dr. Carter, thank you for your testimony. You stated that the overarching message that you want to convey today is that now is the time to move aggressively toward the development and deployment of fusion energy. Can you say more about what is unique about this particular moment in the course of fusion energy development in comparison to, say, 5 years ago or 20 years ago? And can we really expect fusion to make a real contribution to climate action in the United States, for example, given how quickly we need to get to a zero carbon grid?

Dr. CARTER. Thanks for the question. I would say this. The landscape has changed dramatically over the last decade. I will reiterate what I said in my brief remarks. There are really three reasons for why the time is now. The scientific and technical progress that I outlined that positions us to make the next step, the growth of the private sector, that is tremendously important. It puts into place interest from the private sector and pushing commercialization.

And another thing that's very important that we lacked even 5 years ago was a vision and a strategy within the U.S. program to execute and develop fusion energy. To elaborate more briefly, we've advanced significantly in our predictive capabilities for fusion plasmas. We've used these to reach record magnetically confined pressure in tokamaks, for example, used that understanding to enable the record NIF shot that I mentioned, reiterate the CFS result. And, again, this is really a gamechanger for fusion, as Bob pointed out, opening up the operating space for fusion energy.

Again, this—to reiterate the strategy, we haven't developed a new strategy since maybe the early 2000's. The program had been receiving—as a science program, we didn't really have a vision for where to go. With the National Academies' report in 2019 and the recent report by FESAC and by the National Academies to bring fusion to the U.S. grid, we now have a consensus vision for when—where fusion energy development needs to go in the United States, and this is incredibly important.

Chairman BOWMAN. Thank you. Dr. McCarthy, you discuss how fusion energy is a natural progression in the development of nuclear energy technology. I'm wondering if you can elaborate on why fusion energy is the next step beyond advanced fission. What are the potential benefits of fusion compared to fission, including with respect to safety concerns and the challenges associated with radioactive waste?

Dr. MCCARTHY. So absolutely. First of all—and you heard a little bit about this already. Fusion has the potential to provide practically limitless energy. The fuel is readily available, and the byproducts of the fuel, byproducts of the reaction are neutrons and helium for a traditional deuterium-tritium fuel cycle, which themselves are not radioactive but do produce some radioactivity when neutrons, for example, are absorbed by structural materials. But that radioactivity that results from the fusion operation does not have to be isolated for the long periods of time that fission reactor waste needs to be isolated, so that would be one of the advantages.

With respect to safety, fusion reactors are naturally safe in terms of shutting themselves down and don't pose the hazard of widespread release of radioactivity.

And I think, you know, one of the important things—and I think it might have been Troy or Tammy that touched on this a little bit—is energy justice. This fuel, as I said earlier, is readily available and broadly available both nationally and internationally. So I think those are a few of the reasons why it's the natural progression beyond fission.

Chairman BOWMAN. Thank you very much. And my apologies to everyone. I seem to have skipped Sir Dr. Steven Cowley's testimony, my bad. Someone on my team will be fired today.

Dr. Cowley, please provide your testimony. I am so sorry, sir. I will send you flowers. Please forgive me.

TESTIMONY OF DR. STEVEN COWLEY, DIRECTOR, PRINCETON PLASMA PHYSICS LABORATORY

Dr. COWLEY. The flowers are not necessary, sir.

Chairwoman Johnson, Ranking Member Lucas, Subcommittee Chairman Bowman, Ranking Member Weber, and Committee Members, thank you very much for the invitation to testify today. I am the Director of the Princeton Plasma Physics Laboratory and a Professor of Astrophysics at Princeton University, which manages PPPL, the lead national laboratory for fusion and plasma physics. The entire fusion community is deeply grateful to this Committee for its long-standing commitment to the development of fusion energy. It is an honor indeed to appear before you.

We've heard from several people that fusion is very desirable, but do we need fusion? The short answer is yes. Reaching net zero by midcentury will require hundreds of gigawatts of zero-carbon firm electrical generating capacity. Firm means sources that are not dependent on the Sun or wind and can be switched on and off at will. As my Princeton colleague Jesse Jenkins emphasized at a recent PCAST hearing, a truly sustainable, firm energy source is needed. Fusion is one of the very few options and perhaps the best to meet that need and is therefore essential that we move to realize fusion electricity production as fast as possible.

I am more optimistic than at any time during my career that we are on the home stretch to fusion electricity. Why? This hasn't really been mentioned. The last decade has seen a huge change in our scientific understanding of fusion systems. In particular, the advances in theory, algorithms, and high-performance computing have finally made it possible to predict the turbulence that dominates all fusion experiments and has frankly frustrated progress. This is a fiendishly difficult problem, and its solution is a triumph of the DOE-funded program.

But it's more than an intellectual breakthrough. For the first time it is now possible to design and optimize fusion systems on the computer. Current fusion reactor designs all require innovations to make them viable candidates for the first generation of fusion plants. The Princeton Plasma Physics Laboratory with industry and university partners is addressing the need by combining model virtual engineering and the latest fusion science to innovate computation. This modern methodology has been remarkably successful in industry from the new space industry to the automobile industry. And it's a powerful new tool to shorten the time to fusion electricity.

So what should we do now to hasten the arrival of fusion electricity? Dr. McCarthy has emphasized the central importance of ITER, and Dr. Carter has described the community consensus plan, which the leadership of this Committee has wisely requested. I will highlight some aspects of the plan.

The National Academy of Sciences, Engineering, and Medicine earlier this year published a report "Bringing Fusion to the U.S. Grid." That report has two recommendations. And the first one is a very clear, ambitious goal. The Department of Energy and the private sector should produce net electricity in a fusion plant in the United States in the 2035, 2040 timeframe.

The first step toward this goal is contained in the author's second recommendation. DOE 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 that will lead us to an engineering design of a pilot plant that will bring fusion to commercial viability. This is the key. We must urgently form these teams and develop these conceptual designs. It is critical if we are to deliver fusion fast that several conceptual designs are developed. We need to let the ideas compete. By driving design choices in a modern virtual environment, we can work backward to determine what must be done now.

Attractive pilot plants demand high confinement. Thus the promise of superior confinement on the national spheric tokamak experiment upgrade under construction at Princeton and the remarkably high performance of the DIII tokamak at General Atomics, really the highest performing tokamak in the world in terms of per-unit mass if you like must be cornerstones of the U.S. program, cornerstones that will help ITER succeed and reduce the cost and scale of fusion pilot plants.

Finally, we need to accelerate, first, the development of fusion materials for a fusion power plant; second, the technology for making electricity from fusion heat; and third, the systems to breed and separate the fusion fuel tritium in the plant. These issues are being set aside while we develop the plasma confinement systems. If we are to speed fusion electricity delivery, these issues can and should be addressed in parallel with enhancing confinement and the designs of pilot plants.

This Committee had the wisdom to authorize the activities described above in the *Energy Act of 2020* and more recently the *Department of Energy's Science for the Future Act.* We look forward to full implementation and funding of these activities, which will indeed accelerate the arrival of fusion electricity.

Thank you again for your support, and I look forward to your questions.

[The prepared statement of Dr. Cowley follows:]

Fostering a New Era of Fusion Energy Research and Technology Development
Professor Steven C Cowley, Director, Princeton Plasma Physics Laboratory

Chairwoman Johnson, Ranking Member Lucas, Subcommittee Chairman Bowman, Ranking Member Weber and committee members:

Thank you for the invitation to testify today. I am the Director of the Princeton Plasma Physics Laboratory and a professor of astrophysics at Princeton University, which manages PPPL, the lead National Laboratory for fusion and plasma physics. The entire fusion community is deeply grateful to this committee for its long-standing commitment to the development of fusion energy. It is an honor to appear before you.

Do we need fusion? The short answer is "yes." Reaching "Net Zero" by midcentury will require hundreds of gigawatts of zero carbon "firm" electricity generating capacity. That is, sources that are not dependent on sun or wind and can be switched on and off at will. As my Princeton colleague, Jesse Jenkins, emphasized at a recent PCAST hearing, a new truly sustainable firm energy source is needed.[1] Fusion is one of the very few options, and perhaps the best, to meet that need. It is therefore essential that we move to realize fusion electricity production as fast as possible.

I am more optimistic than at any time during my career that we are on the home stretch to fusion electricity. Why? The last decade has seen a huge change in our scientific understanding of fusion systems. In particular, advances in theory, algorithms and high-performance computing have finally made it possible to predict the turbulence that dominates all fusion experiments and has frustrated progress. This is a fiendishly difficult problem, and its solution is a triumph of the DOE-funded program. But it is more than an intellectual breakthrough: for the first time, it is now possible to design and optimize fusion systems *on the computer*. Current fusion reactor designs all require innovations to make them viable candidates for the first generation of fusion plants. The Princeton Plasma Physics Laboratory, with industry and university partners, is addressing the need by combining modern virtual engineering and the latest fusion science to innovate *computationally*. This modern methodology has been remarkably successful in industry – and it's a powerful new tool to shorten the time to fusion electricity.

What should we do now to hasten the arrival of fusion electricity? Dr. McCarthy will emphasize the central importance of ITER. Professor Carter will describe our community consensus plan which the leadership of this committee wisely requested. I will highlight some aspects of the plan. The National Academy of Sciences, Engineering, and Medicine earlier this year published a report *Bringing Fusion to the U.S. Grid.*[2] That report recommends a clear ambitious goal: *"the Department of Energy and the private sector should produce net electricity in a fusion plant in*

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[1] See also discussion of firm energy sources in:
https://www.sciencedirect.com/science/article/pii/S2666278721000234

[2] https://www.nap.edu/catalog/25991/bringing-fusion-to-the-us-grid

the United States in the 2035-2040 timeframe." The first step towards this goal is contained in the authors' second recommendation: *"DOE 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 that will lead to an engineering design of a pilot plant that will bring fusion to commercial viability."* This is the key: we must urgently form these teams and develop these conceptual designs. It is critical, if we are to deliver fusion fast, that several conceptual designs are developed – we need to let the ideas compete. By driving design choices in a modern virtual environment, we can work backwards to determine what must be done now.

Attractive pilot plants demand high confinement. Thus, the promise of superior confinement on the National Spherical Tokamak Experiment Upgrade under construction at Princeton and the remarkably high-performance of the DIII-D tokamak at General Atomics must be cornerstones of the US program – cornerstones that will help ITER succeed and reduce the cost and scale of pilot plants.

Finally, we need to accelerate: (1) the development of materials for fusion power plants; (2) the technology for making electricity from fusion heat; and (3) the systems to breed and separate the fusion fuel tritium in the plant. These issues have been set aside while we develop the plasma confinement systems. If we are to speed fusion electricity delivery, these issues can, and should, be addressed in parallel with enhancing confinement and the design of pilot plants.

This Committee had the wisdom to authorize the activities described above in the "Energy Act of 2020" and, more recently, the "Department of Energy Science for the Future Act." We look forward to full implementation and funding for those activities which will indeed accelerate the arrival of fusion electricity.

Thank you again for your support and I look forward to your questions.

Curriculum Vitae
Professor Sir Steven Charles Cowley FRS, FREng, HonFIET.

Short Bio:

Steven Cowley, a theoretical physicist and international authority on fusion energy, became the seventh Director of the Princeton Plasma Physics Laboratory (PPPL) on July 1, 2018, and a Princeton professor of astrophysical sciences on September 1, 2018. Most recently president of Corpus Christi College and professor of physics at the University of Oxford in the United Kingdom since 2016, Cowley previously was chief executive officer of the United Kingdom Atomic Energy Authority (UKAEA) and head of the Culham Centre for Fusion Energy. He earned his doctorate at Princeton University in astrophysical sciences in 1985 and was a staff scientist at Princeton Plasma Physics Laboratory from 1987 to 1993. From 2011 to 2017 he was a member of the UK prime-minister's Council on Science and Technology. He is a Fellow of the Royal Society, the Royal Academy of Engineering and, was knighted by the Queen of England in June 2018.

Professional Appointments:

2018-	Director, Princeton Plasma Physics Laboratory, and Professor of Astrophysics, Princeton University.
2016-2018.	President, Corpus Christi College, Oxford and Professor (part time), Department of Physics, Oxford University.
2009-2016	Chief Executive Officer, UK Atomic Energy Authority.
2008-2009	Director, UKAEA Culham.
1993-2001 2003-2008	Professor 2000, Associate Professor 1996, Assistant Professor, 1993 Director of DOE funded Centre for Multi-scale Plasma Dynamics. 2004 Department of Physics and Astronomy University of California, Los Angeles
2001-2016	Professor (Part Time 2003 -), Head of Plasma Physics 2001-2003 Department of Physics Imperial College of Science, Technology and Medicine
1987-1993	Research Physicist with Rank of Associate Professor 1992 Staff Physicist 1987, Plasma Physics Laboratory Princeton University
1985-1987	Senior Scientific Officer, UKAEA Culham Laboratory
1985-1987	College Lecturer in Physics, Corpus Christi College Oxford University
Education:	Ph.D., Department of Astrophysical Sciences, 1985 M.A., Department of Astrophysical Sciences, 1983 Princeton University, Princeton, New Jersey
	B.A., Physics, 1981 Oxford University, UK.

Students/Post-docs: supervised 15 PhD students and 13 post-docs.

Professional and Academic Service (Selected):

- Member *Prime Minister's Council of Science and Technology,* 2011 – 2017.
- Member *National Laboratory Directors' Council,* 2018 – ….
- Member *Ecole Polytechnique Federal de Lausanne* Review committee 2019.
- Member *Isaac Newton Institute Scientific Steering Committee,* 2012 – 2016.
- Member *ITER Council Working Group on the Independent Review of the Updated Long-Term Schedule and Human Resources* 2015-2016
- UK Member of Governing Board of Fusion for Energy 2008- 2016.
- Member Prospects for Inertial Confinement Fusion Energy Systems Committee, report "*Assessment of the Prospects for Inertial Fusion Energy*." US National Research Council 2013.
- Chair *Princeton Plasma Physics Laboratory's Scientific Advisory Committee.*
- Judge *Google Science Fair 2012, 2013, 2014, 2015, 2016.*
- British delegate to *Consultative Committee for EURATOM on Fusion CCE-FU. 2008-2013*
- Member of the board of the *Advanced Manufacturing Institute,* Sheffield.
- Chair, Decadal Review of Plasma Science, report "*Plasma Science: Advancing Knowledge in the National Interest."* US National Research Council 2007
- Member of the UK. Fusion Advisory Board 2003 - 2008.
- Member Burning Plasma Assessment Committee, report "*Bringing a Star to Earth*." US National Research Council 2004.
- *Physical Review Letters,* Decadal Review committee, 2002-2004.
- Chair of the US National Research Council's Plasma Science Committee, 1997-2000.
- Physics Survey Overview Committee of the US National Research Council, 1999- 2001.
- DOE Energy Research Strategic Planning Committee 1998.
- Fusion Energy Science Advisory Committee - Review of ITER Physics Panel, 1997.
- Joint Chairman, NSF, Institute for Theoretical Physics Workshop on Plasma Turbulence and Intermittency, Santa Barbara, 1995.

Research Interests:

Fusion Theory, Space and Astrophysical Plasmas, Energy Policy.

Awards, Honors (selected):

2020	Honorary Fellowship, Corpus Christi College, Oxford
2019	Honorary Doctor of Science, University of Lancaster
2018	Knight Bachelor, Queen's Birthday Honours
2015	Honorary Fellowship, Institute of Engineering and Technology.
2014	Fellow of the Royal Academy of Engineering
2014	Fellow the Royal Society
2012	2012 Glazebrook Medal of the Institute of Physics
2009	Honorary Professor University of York
2004	Fellow of the Institute of Physics, UK.
1998	Fellow American Physical Society
1993, 96, 97, 2006	Physics Department Award for Excellence in Teaching, UCLA
1984-85	Charlotte Elizabeth Proctor Fellowship from Princeton University
1981-83	Harkness Fellowship
1978-81	Scholarship from Corpus Christi College, Oxford University

Over 190 publications including 24 Physical Review Letters. Google scholar page:

http://scholar.google.com/citations?user=zJrztlwAAAAJ&hl=en

Chairman BOWMAN. Thank you so much, Dr. Cowley.

I now recognize Mr. Weber for 5 minutes of questions.

Mr. WEBER. Well, thank you, Chairman.

Gosh, I don't—pardon me—quite know where to start. I'll start backward, I guess, with Dr. Crowley, although you said he's been knighted, so we're supposed to call him "Sir." What I want to know from Dr. Crowley is whenever he testifies, does he get like a surcharge? That's what I want to know.

Dr. Crowley, you said something very interesting. You actually put a timeframe on it, a 2035 to 2040 timeframe. Are supercomputers going to be needed to hit that timeframe?

Dr. COWLEY. Absolutely. That's the big advantage we have now that we didn't have, you know, 25 years ago, and it's what the Department of Energy has spent a great deal of time developing, yes. If you look at the way engineering is developed in the new space industry and in——

Mr. WEBER. My pods are about to die. I'm sorry, go ahead.

Dr. COWLEY. Sorry. And also in the new development of new nuclear reactors. It's the use of the computer to shorten the development time is absolutely critical.

Mr. WEBER. Well, thank you for that. I'm getting a note that my AirPods here are low on battery, so let me jump over to Dr. Carter if I may.

Well, first of all, let me say it's no secret U.S. leadership in fusion research is being threatened by large investments made by other nations. Luckily, I'm of the opinion—I think we would all agree—that the United States has the advantage of extensive public-private partnerships. In fact, one of the witnesses said that. This makes it easy for companies wanting to pursue fusion energy to utilize DOE's world-class facilities and research. The more players in the game, the higher the likelihood someone succeeds. And in fact, Dr. Crowley, you—or Sir Dr. Crowley, you said that several critical designs needed to be developed and then work backward to pick the best one, so I'm encouraged that we're all kind of on that same wavelength.

But I want to go to Dr. Carter. Dr. Carter, based on your work chairing the FES Long-Range Planning Subcommittee can you give us a sense of what level of investment is required to compete with these international investments, please?

Dr. CARTER. Well, I can just comment on what we're seeing in the landscape elsewhere. One important program that's been brought up already, the U.K., is the STEP (Spherical Tokamak for Energy Production) program. That investment over the next few years is on the order of half a million dollars—half a billion, sorry, dollars. To really get—kick that program off, it's also been—that level of funding has helped attract companies, so, as was already mentioned, General Fusion decided to site their program at Culham Labs because of that, the resources provided, and the ability to be there.

If you look more broadly beyond that one program, the United States is falling behind. The level of investment that was, you know, authorized by this Committee is the level of investment that will put us on the right path, that accelerated path, and put us in line more with what the investment is across the world. You look at China, the investment there is also tremendous both from the public and private sector, and, you know, they're basically building one of everything is their approach to try and—those devices they're building are devices that are ideas that have come out of the U.S. program. In a sense, U.K. and China are beating us to the punch on our own plan for fusion energy development.

Mr. WEBER. Well, so with that in mind—thank you—this is for all witnesses, but I don't have a clock in front of me. How much—Mr. Chairman, how much time do I have left?

Chairman BOWMAN. One minute, 25 seconds.

Mr. WEBER. OK. If we cannot match other nations dollar for dollar, what steps if any can we take to maximize the investment of dollars do we have? And, Dr. McCarthy, I'll go back to you.

Dr. MCCARTHY. So I think it's really important—this has been brought up—is these public-private partnerships. And I'll emphasize the national teams that Dr. Cowley talked about because each of these members of these teams brings in a different sort of perspective. Industry has the goal-driven point. National laboratories have a breadth of expertise that doesn't exist elsewhere. Universities have the broad—or the deep research expertise. You put all of that together, a diverse team that looks at things from different angles, that's what's got to happen because these are very challenging problems to solve. Each of these areas has very challenging problems to solve. So I would say that is the place to go, programs like INFUSE, which already exist, but potentially a larger INFUSE program.

Mr. WEBER. OK. Thank you for that. Dr. Mumgaard, same question for you.

Dr. MUMGAARD. Yes, I echo the other panelists, that for the United States to succeed, we're not going to be able to just match, you know, China dollar for dollar. We're going to have to leverage what we're really good at. And what we're really good at in the United States is really at the intersection of different fields and different types of enterprises. So entrepreneurship has shown over and over again that it can pick winners and that can take risks and move very, very quickly. At the same time, it's not going to do what the national labs do in terms of deep expertise. It's not going to replace universities. So if you put them together, you get a really, really powerful combination. And we've seen that in pharmaceuticals with NIH (National Institutes of Health) working with the pharmaceutical companies. We've seen that in aerospace. We've seen that over and over again that that's how you produce really the fastest least-resource-intensive path to a solution, and particularly a solution that can win the market. It's not good enough just to build a pilot plant. We need to build a pilot plant that people want to buy. And then we need to make a pilot plant that people can build many, many of. And so you need that whole spectrum all in one spot, and the United States is historically very good at that.

Mr. WEBER. Well, good. I appreciate that, and, Mr. Chairman, I yield back. Thank you.

STAFF. Ms. Stevens is recognized.

Ms. STEVENS. Great, thank you. Thank you, Mr. Chair, and thank you to panelists for just a great hearing.

Obviously, in your testimonies you touched on and cited legislation by this Committee to better guide the Department of Energy's fusion research activities. This obviously includes the Committee's *DOE Science for the Future Act,* which our Chair discussed, as well as significant investments in fusion R&D and facility construction that we included in the contribution to the *Build Back Better Act.*

Just wanted to take a scope from, you know, a handful of you, Dr. Ma, Dr. Mumgaard, Dr. Carter, and Dr. Crowley. You know, what might we be missing from legislation at this point, gaps in the laws that we should be considering to address at this point? Dr. Ma, go ahead.

Dr. MA. Thank you for the question. I'll just start by saying we're very, very appreciative of the support of the House and in particular this Committee for both the long-term sustained funding for the NIF and for your commitment to establishing an inertial fusion energy program.

There are a few areas that I know the fusion community would like a little more support on. I'll actually hand it over to Dr. Carter to touch on.

Dr. CARTER. I can take it from there. I mean, I'll add my thanks. I think these laws align very well and bills with what the priorities are expressed are important and extremely helpful. Where we may need more help—and I think this I'll pass to Dr. Mumgaard to expand on—I think we need ways to expand and improve and better ways to partner with the private sector to really get this done, so any help we can get to improve that within the DOE would be helpful.

The other issue I'll raise is to accelerate the timeline, we need to find ways to speed up development of needed facilities, experimental and testing facilities. So currently, you know, we can look at a decade or more to get an important facility built in the current framework. We need to speed that up. And likely the answer there, too, is finding ways to partner with private—the private sector. So any assistance in those two issues would be very helpful.

Dr. MUMGAARD. Yes, I'd agree the legislation has been extremely helpful. It's given clear directives. It's set the United States on a strategy and it's authorized new facilities, but we haven't implemented it yet. So if you actually look at what is in the DOE budget proposal, it's not aligned with the legislation, so we've got to get that fixed. I know that's not the role here, but it is something that we're very excited to see happen.

Additionally, there are some elements that have been proposed that we need to maybe tune a little bit, so, for instance, the public-private partnerships. There's multiple ways to do that, and we've seen that get tried across the DOE, NASA, and if we think creatively about how to do that, things like other transaction authorities, things like new temporary types of offices—or programs inside the DOE, we can probably tune these pretty well to get really the best of both worlds and the key challenge being that this is new to the DOE Office of Fusion Energy Sciences, that this is——

Ms. STEVENS. Yes.

Dr. MUMGAARD [continuing]. Not what we've done previously, so we have to learn new skills. But we can pull those skills in from, say, ARPA-E (Advanced Research Projects Agency—Energy), which the legislation did say go work with ARPA-E and NE (Office of Nuclear Energy). So those types of expansive, collaborative, new types of thinking about how to set up programs, that's very, very helpful.

Ms. STEVENS. Yes. And the clock's back. OK, let's see. I've got 1:20. It's hard to tell where I am on the time. But I guess my follow up question to all this—and thank you, really helpful feedback there and always interesting when we try and engage in the, you know, directive of the public-private partnership space. But I'm curious about that last point that you were making, Dr. Mumgaard about costs and materials and particularly, as Dr. Crowley, you know, just answered a question related to high-performance computing, you know, supercomputing is very expensive. What else do we need to know about the accessibility of materials, cost, storage, access points, you know, multistate collaborations, things along those lines?

Dr. MUMGAARD. Yes, I—I'll jump in there.

Ms. STEVENS. Yes.

Dr. MUMGAARD. You know, fundamentally, fusion is intriguing because the—you know, the materials that a fusion machine are made out of are steel and concrete. And so in the long run it should be economic. It's—if we get better——

Ms. STEVENS. Well, steel is expensive now though, you know, Dr. Mumgaard.

Dr. MUMGAARD. Yes, but per unit—if you think about it in terms of per-unit of——

Ms. STEVENS. Yes.

Dr. MUMGAARD [continuing]. Energy produced, it's much lower than even a fossil industry building in terms of the capital. So you have an advantage over the long run. And over the near term, though, reiterating what Dr. Cowley said, the advances in computing mean that—you don't have to build as many machines upfront, which you can do many, many more experiments in the computer than you can in real life, and that's a big time-saver and a big cost-saver even though——

Ms. STEVENS. Yes.

Dr. MUMGAARD [continuing]. It might be a case that supercomputing——

Ms. STEVENS. Well, the access might be expensive, but I'm out of time. Thank you, Dr. Mumgaard, really looking forward to the rest of the questions today.

With that, Mr. Chair, I'll yield back.

STAFF. Mr. Lucas is recognized.

Mr. Garcia is recognized.

Mr. GARCIA. Thank you, Mr. Chairman, and thank you to the witnesses, very interesting, intriguing technologies, and I think many of you are hitting it right on the head, a very hopeful era in our Nation's path to clean energy—sustainable clean energy.

Dr. Ma, I wanted to touch on what you are doing, this gain of energy of .7, 70 percent that you have achieved. Can you talk to sort of what are the next incremental goals that your team is looking to achieve? And then also, can you talk to—this is a record that's tied a previous achievement out of the U.K., right, but they did this back in, what, 1997. So can you kind of give us a lay of the land as where are—I'll call them competitor nations are in this progress? What led to the U.K. effectively stalling out at .7 and not achieving higher, or have they in other forms, in other technologies? And what do we need to do either differently or in addition to what's already been done in order to get to ignition? Just kind of give us an overview of the roadmap to at least 100 percent ignition.

Dr. MA. Thank you, Representative Garcia, for the question. This achievement that we've achieved of a gain of .7 means that we've effectively gotten close to the same amount of energy out of the target that we put in with the laser. And from a physics perspective what that means is we have been able to start the—use a flame front to basically start the ignition of a piece of wood to burn. So effectively we are there.

And the next steps for us here on the NIF are we are repeating the shot now to demonstrate robustness, repeatability, make sure that we understand the physics performance and the key metrics to—that affect that performance. And we do believe that with the NIF we will be able to demonstrate much higher gains coming up. And in fact this is part of our NNSA mission to achieve very high fusion yields for those missions.

You're right that this does compare to a result out of the U.K. back in 1997 on a tokamak. However, our results on the NIF is the first time that we have had what we call a burning plasma where the energy coming out of the plasma exceeds the thermal heating that went in. And now the burn is very robust. And so it's like that flame on that piece of wood is growing.

I will have to defer to my colleagues to explain why that result has stalled on the tokamaks. I'm not completely clear. But I think we all know that with the current progress that we've had in emerging technologies, computation, as Dr. Mumgaard has referred to, where we're poised to make a lot of great progress soon.

Mr. GARCIA. Is it fair to say that 200 percent or so is a rough target to effectively offset some of the efficiency losses through the process for actually having greater energy out versus in or is that not fair and, Sir Cowley, I see you there looking to speak. Go ahead, sir.

Dr. COWLEY. Oh, I guess I should speak up for the U.K. result. I used to run that facility. And the—it was of course an immense result in 1997. But the results on NIF is actually very interesting because the heat from the fusion is contributing to the gain whereas that wasn't true in the European facility in 1997. And that's what we mean by burning. And so if this can be improved at NIF, they will be making most of the fusion happen because they made fusion happen. And that is—that's the goal that we really want to do.

Now, what happened in the U.K. program was that those results resulted in the design of ITER because ITER is—that machine is called JET, the Joint European Torus, and ITER is just two times JET.

Mr. GARCIA. OK.

Dr. COWLEY. That shape and that design is, you know, at higher field, for instance, is roughly what SPARC is. That's the most common configuration at that time. And it's really been sparked by those 1997 results on JET.

Mr. GARCIA. Great, OK. So we are leveraging it and synergizing. I'm out of time, Mr. Chair. I'll yield back.

STAFF. Mr. McNerney is recognized.

Mr. MCNERNEY. Well, I thank the Chair, and I thank the witnesses. I've been a longtime and enthusiastic supporter of fusion energy starting with work at Los Alamos National lab when I was a grad student. And I believe fusion development is moving quickly and that, once commercially available, will be an important contributor to our baseload power needs.

The national labs, higher educational institutes, private companies in the United States are performing some of the most critical and groundbreaking technology in fusion in the world. So in testimony today we've heard about two of the U.S.-based magnetic fusion facilities. I was fortunate earlier this year to visit the DIII-D in San Diego and witnessed some impressive research.

Dr. Cowley, in your testimony you mentioned the promise of DIII-D, tokamak, and the work at Princeton. How important is the continued improvement of both of these facilities to the nascent U.S. fusion enterprise, and what scale investments you think are necessary?

Dr. COWLEY. The DIII-D tokamak pound for pound is the highest performing machine in the world. And that's because U.S. scientific leadership has allowed us to understand how to optimize the situation. And one of the things that we need to understand is that fusion will be cheaper if we can make confinement better. And that's really being pushed forward immensely by General Atomics. The machine we're building at Princeton is to try and leverage that in a more compact configuration so that we can make smaller, cheaper, faster fusion devices. It's true that we may have enough confinement now to go all the way to fusion, but if we get more confinement, it'll be a better fusion reactor when we get there. And so it's very critical to keep the confinement program going because that way we'll get the best out of ITER and we'll get the best out of our pilot plants.

Mr. MCNERNEY. Thank you. Do you think there's any policy change that would facilitate the DIII-D program?

Dr. COWLEY. Well, I think that it would be good to see DIII-D get an upgrade because I think that the team that works there has had some of the most amazing breakthroughs in the science. And, you know, this is not my team so I can say it from a distance. And to keep that going as we're approaching ITER operation by giving, you know, some kind of upgrade to that device would be—I think would greatly improve our chances of getting the best out of ITER, for instance, and the best out of SPARC and the best out of the pilot plant.

Mr. MCNERNEY. Sure. Sure, thank you.

Dr. Ma, it's good to see you this morning. I visited the NIF on multiple occasions starting in 2007 and was more than excited to hear about the breakthrough this August. In your testimony you commented on how the mission at the Lawrence Livermore National Lab imposes limits on what research can be pursued at the lab. Do you have recommendations for how LLNL and other national lab sites can translate breakthroughs like the one at Livermore this August into long-term fusion energy?

Dr. MA. Thank you for the question. Yes, so the result that we recently had on the NIF demonstrates the basic scientific feasibility of laser-driven inertial fusion. And with that we can now start to also validate our simulation codes in this regime of very high neutron yields. And it gives us a great amount of confidence that we can now use our codes to further scale to different ignition designs and test out alternative concepts.

Now, the NIF is currently the leading experimental capability for studying these ignition schemes relevant to inertial fusion energy at near to full-scale, and so because of that, it's very valuable and we should absolutely use it to test out other experimental concepts that can help advance our overall physics understanding and continue to validate our simulation codes.

Mr. MCNERNEY. So how is artificial intelligence being used?

Dr. MA. That is a wonderful question. Our experiments are so incredibly complex. There's sometimes 10,000 different physics parameters that might go into defining a particular experiment. So we absolutely need to use high-performance computing to help us to do the best experiment possible and use artificial intelligence and machine learning to get a better handle on all of those different physics parameters and use that also for advanced capabilities such as multimodal data understanding, so taking in all our different types of information and building a more complete picture. And then also, as we do experiments on these new facilities, subscale facilities coming up where we can do experiments much, much faster, we can match that to machine learning to extract greater insights.

Mr. MCNERNEY. Too many dimensions for the human mind maybe. Thank you very much, and I yield back.

STAFF. Ranking Member Lucas is recognized.

Mr. LUCAS. Thank you, Mr. Chairman. As I mentioned in my opening comment, I'm a strong advocate for investing in U.S.—the U.S. contributions to ITER, the world's leading international research collaboration on fusion energy, which received continued bipartisan support from this Committee. In your testimony you note that while the ITER project is physically located in France and much of our contribution to the project are in fact used to support research, but much of our contributions are used to focus on research here at home. Dr. McCarthy, can you please expand on these comments and explain—providing specific examples if you can—ways in which U.S. contributions to the ITER program have directly contributed to scientific discoveries and successes in the U.S. fusion community? And along with that, what would it mean to the U.S. research community if we were to fail to meet our commitments to the ITER program?

Dr. MCCARTHY. OK. Thank you very much for that question. So one of the things that the recent National Academies report looked at was specifically how ITER is contributing and will continue to contribute to fusion development broadly. And let's talk, for example, about magnet technologies. We heard about Commonwealth Fusion's recent accomplishment. This is a great step toward being able to have more compact and more cost-effective devices.

The research that was done specifically for the superconducting magnets for ITER is directly providing the base for those sorts of accomplishments. And one of the things I think it's really important to point out is as you actually build things, as you scale things up—because ITER was designed based on known technologies all demonstrated at some scale, sometimes at a much smaller scale, you learn things when you scale up. You learn things that you wouldn't expect. And so there's a lot of engineering challenges. And we tend to, in the fusion program, talk about the plasma, but that is not all there is. Now, we've got to look at the bigger picture. It includes things like magnets but also includes things like blanket technologies materials and things like that.

Other examples, another one is fuel cycle and continuous fueling because ITER will run on a deuterium-tritium fuel cycle, and there's a lot of work that's being done there in terms of the fueling, disruption mitigation, how do you dissipate the heat in and off normal event? That research is being done for ITER. And there are many other things as well. Plasma heating, that is another area.

But it's really important in that practical application, writing specifications that industry then can develop this hardware that meets these very exacting specifications that fit into this machine. That's preparing our U.S. industry for a future fusion industry.

Mr. LUCAS. Thank you. And I guess I address my next couple questions to whoever on the panel would like to touch it. Given the panel's various experiences of DOE's Office of Science's Fusion Energy Sciences Advisory Committee, do you have any recommendations on how the Fusion Energy Sciences program could be more—could more effectively engage with other relevant programs within the Office of Science and, for that matter, the rest of the Department if necessary?

I maybe—may—could I just go to Dr. Ma first, and I'd like to hear your thoughts on that, and then turn to Dr. Carter with the same question. After that, whoever else would like to touch it.

Are you muted, Dr. Ma, or am I muted?

STAFF. Dr. Ma, your audio is out.

Dr. MA. Apologies. How's this? Can you hear me?

STAFF. Yes.

Mr. LUCAS. Yes.

Dr. MA. OK. Yes.

STAFF. OK.

Dr. MA. Apologies. Yes, I would say that there—a recommendation of the report and a feeling amongst the community is there are many great opportunities for our different agencies to work more closely together. There are some great examples now of Fusion Energy Sciences doing joint calls for proposals with NSF or with the NNSA, and that has—those have been hugely valuable and fruitful for the academic community. We can also work more closely with ARPA-E to harness public-private partnerships as well. And so this is something that we have not fully realized within Fusion Energy Sciences, and it's a very economical way as well to grow the overall research portfolio.

Mr. LUCAS. And if the Chairman would humor me, could I ask Dr. Carter that same question?

Dr. CARTER. Yes, I'll just amplify——

STAFF. Yes, sir.

Dr. CARTER [continuing]. What—oh, sorry. I'll just amplify what Dr. Ma said. I think that the—we brought up already the need to do better in the sector—interacting with the private sector. ARPA-E does that well, and there's already a collaboration with FES. I think that needs to be amplified. We also look for help from other agencies that are doing this already, so look at Office of Nuclear Energy within DOE, look at NASA. There are other programs that we can learn from. We'll need unique ideas for Fusion Energy Sciences, but we can learn from those programs and try to implement them within DOE.

Mr. LUCAS. Thank you. And thank you, Mr. Chairman. I yield back.

STAFF. Mr. Casten is recognized.

Mr. CASTEN. Thank you, Mr. Chair. Thanks so much to all our witnesses here.

Dr. Mumgaard, in your testimony you mentioned that if—I guess you expressed a concern that if the United States doesn't act now, we run the risk of private companies investing and constructing their fusion power plants elsewhere in the world and that Congress and DOE should move quickly to fully fund and implement milestone-based cost-shared development programs to ensure that the first fusion power plant is built in the United States.

Based on the recommendations from National Academies and FESAC's long-range planning, do you believe that the Department of Energy is at a point to support these commercialization plans?

Dr. MUMGAARD. The legislation lays out a really good pathway, but we've not yet seen the activity from the Department itself, so, for instance, there was a request for information about the—how to maybe implement a cost-share program, what various private entities thought would be helpful. That was submitted almost a year ago, and we've not yet seen, you know, any sort of calls or establishment of an office to try to enact those things.

And so, you know, right now, it's—the signals are not great. And I think that, you know, had a strong contributing factor for people looking elsewhere. You know, is the United States' fusion program going to enact these and put in these new programs and these new facilities, or do you go with someone like the U.K. who's got steel in the ground and programs that are open and taking applications?

Mr. CASTEN. And just to be clear you're talking about, you know, the N equals 1 commercial plant, right? I mean——

Dr. MUMGAARD. Yes.

Mr. CASTEN [continuing]. You know, I—in another lifetime I did a lot of stuff on technology deployment and, you know, the escrow for power generation is always about 20 years from N equals 1 to 50 percent penetration. That was true for air derivative gas turbines, combined cycles, the wind turbines that my friend Mr. McNerney was involved in. Are we—assuming we got to N equals 1 first, are we doing enough to actually make sure that we ramp up that curve if we are in fact going to be a meaningful part of decarbonizing by 2050?

Dr. MUMGAARD. Yes, it's a great question. And you're exactly right. You know, N equals 1, it gets you, you know, only started. You also have to the policies in place to be able to scale that once you have success. And so in the United States we have a strong history across other energy technologies of things like the Loan Guarantee Office, for instance. You know, how do we get fusion when it's ready ready for the Loan Guarantee Office? We also need to ensure that we have the right regulatory treatment. The U.K. has leaned heavily into that and produced a preliminary report on how they intend to do it, and the United States' NRC (Nuclear Regulatory Commission) is also taking a look at that in part of a public hearing process.

So I'd say that, you know, the longer term view is we're well-positioned, but this intermediate-term view is a bit uncertain.

Mr. CASTEN. OK, thank you. Dr. Carter, I want to get your thoughts on the same topic. You—you know, you made some similar comments in your testimony that a consensus FESAC's planning made recommendations for DOE action to reorient the U.S. fusion program. Do you have any recommendations, Dr. Carter, for ways that the Office of Science can improve its management of Fusion Energy Sciences going forward?

Dr. CARTER. Yes, well, we have a—we now have a vision that needs to be embraced. We need DOE to implement that plan and work with us in this direction that we know is necessary to realize fusion energy on an aggressive timeline. I think that there's likely need for change in the structure of the FES program. I already mentioned the need to grow. We have programs like INFUSE that are doing good things, but it's a very small program now. We need to look for other mechanisms to do private-public partnership, and that needs to be developed quickly.

Mr. CASTEN. OK. Well, thank you both very much. Huge amounts of support for what you're doing, and I'm a big fan of the Loan Program Office. And if there's anything we can do to help make sure that that's structured to get that ramp up once we get to that first commercialization, please let us know and keep in touch. Thank you both, and I'll yield back.

STAFF. Mr. Feenstra is recognized.

Mr. FEENSTRA. Thank you, Chairman Bowman and Ranking Member Weber. Thank you to each of the witnesses for their testimony and sharing their extensive research and experience with us.

You know, the field of fusion energy holds incredible potential for our energy grid, and I'm so excited about it. The breakthroughs made since *DOE's Research and Innovation Act* in 2018 and especially just this past year are just incredible and outstanding.

The DOE's Ames Laboratory back in my home district is a world leader in materials science innovation. Several of our witnesses today mentioned in their written testimony the importance of developing new materials that can withstand the extreme condition of fusion reactors.

So my question is to Dr. Crowley and then also Dr. McCarthy, if you could answer the same thing after Dr. Crowley. Do you have any recommendations on how to improve coordination with materials science experts and accelerate the development of these materials? How could the DOE and its national laboratories be more—or more effectively contribute to this effort?

Dr. COWLEY. So, I mean, this is a very interesting problem because we've done a bunch of very low-level studies on the materials as they're damaged in—by the neutrons that come out of fusion, but we've never had a test facility to be able to produce the data in which we can normalize our models onto that. And DOE has started a process to produce what's called a point neutron source to actually test materials. If you want to attract scientists to come into this field and help us solve the problem of getting optimum materials for fusion, some data would be fantastic. So getting that point neutron source going, right, which I believe could be done in a matter of a few years, right, and getting some data from them so that we finally know whether our projections of the lifetime of the raw material in the fusion reactor are good or not, that's an easy no-brainer to speed fusion forward.

Mr. FEENSTRA. And, Dr. McCarthy, your thoughts on that?

Dr. MCCARTHY. Yes, I absolutely agree with Dr. Cowley. And I want to talk a little bit more about why we need this. So if you look at the fusion reaction, the deuterium-tritium reaction, you get neutrons, very energetic, 14 MeV. You can compare that with the energy of a fission neutron when it's born, and that's 2 MeVs. So you can just think about how that 14 MeV neutron is going to do more damage to the material.

So we do a lot of testing in fission reactors, but we're limited—we can do testing in spallation sources as well, but we're limited because the energy, the spectrum isn't prototypic. So when you look at actually developing practical, deployable fusion energy, competitive fusion energy, you've got to make sure that you don't have to keep changing out the first wall, for example. You don't have to keep changing out different components. Fission reactors operate on over 90 percent availability, and that is because they have optimized things. They're down very, very rarely. We have to be the same way. So developing these materials is important, and bringing—for example, at Oak Ridge National Laboratory, we bring in our materials experts who are not necessarily nuclear materials experts because they provide a different sort of perspective. And I go back to these diverse teams. So bring them together, agree with Dr. Cowley on this fusion prototypic neutron source. That is going to be key to taking everything that's being done now and getting to practical, competitive fusion energy.

Mr. FEENSTRA. Well, thank you for that, those comments. So, Dr. McCarthy, one more thing. So you're the Director of the U.S. Project Office of ITER, but ITER's central team is made up of seven core countries, and an ITER staff has scientists, engineers, and staff from all across the globe. I assume each of these countries have different incentives to drive research into fusion energy, as well as barriers to expanding the research. So what do you see? What are some barriers that we have here in Congress that we can look forward to or look at removing, you know, through new policies? Or which new policies would possibly help?

Dr. MCCARTHY. So, first of all, what's fascinating is when you work in an international project like this—and I've been involved in fusion for half of my career starting with graduate school—scientists and engineers want to do the same thing. We're all focused on the same sorts of goals. Now, all of us do have different politics that we have to deal with. They're actually shockingly similar. And I can tell you my 3 years in Canada told me that, huh, their government is a little different but it's not that different.

So one of the challenges that we in the United States face is—I think as everybody is aware—appropriations have been lower than what was baseline for the ITER project. And so in some areas we had to prioritize things that were on critical path and delay some other things. Recent appropriations have allowed us to do some catchup, and that has been very much appreciated, but we're still $97 million behind. So we're looking at how do we ramp up? How do we be a good partner in ITER? And how do we really maximize the benefit from being a partner in ITER? So I would say that that—that certainly is one of the areas.

There are also complexities around any sort of international project having people—we want to have people in the United States when ITER operates, and there is just practical considerations in how you do that from a tax perspective and things like that, so really a big range of things.

Mr. FEENSTRA. Thank you so much for your comments, and I yield back.

STAFF. Mr. Lamb is recognized.

Mr. LAMB. Thank you, and thank you to all of our witnesses for joining us.

Dr. Mumgaard, I want to say congratulations like many others have, I'm sure, about the successful test this summer. And I just wanted to ask about—your testimony touched on the importance of the cost-share milestone-based approach that was reflected in our *Energy Act* at the end of last year. And I was wondering if you could just say a few words about why that's important and what it's—what is important for us to make sure that DOE does going forward consistent with that approach?

Dr. MUMGAARD. Yes, so that approach is from the NASA COTS (Commercial Orbital Transportation Services) program. Also, it has elements that come from the advanced reactor program. The key thing here is that you want private industry to do what it does really well, which is to focus on goal-oriented execution, so, you know, put goals down, execute to those goals as fast as possible. And private industry is, you know, willing to do that and take the risks that are part of doing such a milestone-based approach as long as that, you know, when it gets there, it knows it's part of an ecosystem that's going to help it get to the next step.

And so in that cost-share program the key things are, you know, don't have the public program dictate exactly where to go or exactly how to get there but do have the public program be alongside so that when you do get there, you—or if you run into problems along the way in terms of the science and engineering, you get some help. And so it's really not just about money, it's not just about help. It's really about how to tie those together in a way that really frees up the private sector to do what it's really good at without duplicating the work the public side is doing while still bringing the public side along so that the public side can also then reap the rewards of having those new types of facilities. And, you know, that worked to very, very good effect in low-Earth orbit, which, you know, had a higher TRL (technology readiness level) level of than fusion does today, but the principles are still really applicable.

Mr. LAMB. And going forward, what is the sort of important thing to make sure that DOE kind of stays on track or puts the money in the right pots, or how would you say we should be thinking about this for like the next 5 years?

Dr. MUMGAARD. Yes, so thinking about it as—we want to be sure that we do a portfolio, so this is not just pick one. This is do a portfolio approach and run a process that doesn't just look at, say, only the scientific piece or only the piece that's really related to what DOE already does. Instead, run a process that looks holistically. Does this get to a point that does—that has some commercial validation in it? Are the people that are reactor developers, are they interested in this? Is the—are the utilities interested in this? And make sure we have that viewpoint so that it's not just is the science interesting or is the engineering interesting. We need to be able to balance those views. And the best way to do that, of course, is a portfolio where everyone comes, lays their cards at the table, and we look at the different profiles of economic and technical and scientific risk, and we choose a few that really span that. And that'll give us a good shot at this.

Mr. LAMB. Great, thank you. That kind of leads a little bit into my next question, which is about what the manufacturing needs and the manufacturing footprint could look like later. My State Pennsylvania I think is the biggest State for manufacturing in the traditional fission pipeline when it comes to civilian reactors and Navy work. We're certainly up there. And one of the things I want to make sure of is that we are well-positioned for both, you know, whatever is coming in the advanced nuclear fission world and in the fusion world. Do you have any thoughts on the way that the current supply chain could prepare itself for, you know, being a fusion supply chain in the future?

Dr. MUMGAARD. Yes, it's a great question, and it's something that we as industry think a lot about because for us to be successful, it means we have to build many, many, many power plants. Now, if you want to decarbonize, you're always talking about thousands of power plants independent of what technology you choose, and so you have to be sure that you're able to fulfill that in the long run, so you can't make choices that aren't manufacturable.

Fortunately, fusion has a couple of things going for it. You know, it—one, you know, you make a few things and, you know, you make thousands, not billions. And those things are high-value and they take skilled laborers in many ways similar to like an aerospace endeavor. And in fact you see a lot of crossover in the private sector between aerospace investors and staff into fusion companies for that exact reason, which also means that the manufacturing exercises are things like building turbines or building aircraft components where they are, you know, manufacturing in terms of milling and forging metals. And also an area that you can really take advantage of, advanced manufacturing techniques that are up-and-coming, 3-D printing, better heat transfer materials by design. All of that impacts fusion in the same ways it impacts any other sort of mechanical engineering, structural engineering, thermal engineering, heavy type of industry. And so we see a lot of crossover there.

Mr. LAMB. Any other witnesses want to address that? I thought Dr. McCarthy kind of touched on the manufacturing piece as well, but I didn't know if you had any specific ideas about, you know, either government programs or things that sort of traditional nuclear companies could do to get ready for this era or to take advantage of it when it's here.

Dr. MCCARTHY. Yes, absolutely. So, first of all——

Chairman BOWMAN. If you can be as brief as possible.

Dr. MCCARTHY. Absolutely.

Mr. LAMB. Go ahead, sorry.

Dr. MCCARTHY. So, first of all, there's a lot of similarity in components and the specifications and the need to meet the QA (quality assurance) between fission and fusion. And so if you look at ITER, for example—and we do have procurements placed in your State of Pennsylvania—those sorts of activities are getting the industry ready. There's a lot of crossover. It's a small percentage of it that is really specialized that would take additional training.

Mr. LAMB. Glad to hear it. Thank you, Mr. Chair. I yield back.

STAFF. Mr. Meijer is recognized.

Mr. MEIJER. Thank you, Mr. Chairman, and thank you to all of our witnesses here for joining and sharing. This has been a really interesting conversation. And I think we're all incredibly excited at the potential here, you know, for fusion. You know, we see the news articles from time to time and having a layman's understanding, it can be hard to get a little bit of that perspective of scale and potential and when that future is realizable, so the possibility that we can have generation in the 2030's could be—I think it's personally incredibly thrilling.

But I want to piggyback on what my colleague Mr. Lamb had asked about in terms of staff and talent in order to support this growing field and industry moving forward so that if we are reaching that point where there is commercially viable on-the-grid sources of fusion energy, how do we make sure that, as we scale that up, that we have the requisite talent in order to do so.

So, you know, I'm proud to represent Michigan, specifically west Michigan but just outside of our district is Michigan State University's FRIB, the Facility for Rare Isotopes, which supports the nuclear physics mission at the Office of Science within the Department of Energy. The facility draws talent from across the country and also across the world in order to advance discoveries of both rare isotopes, nuclear astrophysics, fundamental interactions, and applications for society, whether it's in medicine, homeland security, industry, or, in this case, leading toward energy production as well. So how can we expand the existing fusion R&D facilities so we're able to attract talent from across the country and across the world and also prepare that for the next generation?

Dr. COWLEY. One of the—that's a very good question, and I think what we've discovered in the last few years at Princeton—and I know at MIT they've discovered the same thing and at UCLA—is that there's a flood of young people coming into the field because they recognize that this is going to be needed to do something absolutely amazing for the planet. And so we have, you know, tripled our applications to our Ph.D. program.

The other thing that the national lab has done—we've done at Princeton is to initiate an apprenticeship program because to make fusion systems work is not just about having, you know, Ph.D.-level physicists or whatever but you've got to have people who think with their hands and are able to construct anything and make anything work, right? And we've been running out of technicians at Princeton Plasma Physics Lab as they age out, and so we started an apprenticeship program with the State of New Jersey and started to train, you know, apprentices on a high level, engineering skills that are needed to do this. This is the kind of work force that we need to make fusion actually happen.

Mr. MEIJER. And I want to open that question up to any of the other panelists but just very quick on that front, I also want to add in—and maybe this is a brief follow up and could be incorporated with the others—who are we competing with the most? We mentioned the U.K. earlier as somebody who seems to be taking a slight step ahead, and obviously we have, you know, great competition with China on this front and many others. But on the talent front specifically, who are our greatest competitors?

Dr. MUMGAARD. So on the first question around the pipeline, I think it's really important to recognize that, as we make investments into these types of facilities that are recommended in the report, the prototypic neutron source and some of the material science elements, those are going to produce fusion generalists that are going to be Ph.D.'s and master's that come out of there, and they're going to come out from all over the world and from all over the United States in terms of universities that participate in those programs, and that's really the feedstock that someone like I as an industry wants to see happen because those people then can enter into, you know, our growing industry and train other people, people that we pull from the aerospace industry or from the traditional nuclear sector, train them up on what fusion is like and the different principles. And so it's not just the, you know, Ph.D.-level scientists. It's the whole spectrum that needs to grow if this is going to take off.

In terms of where we're competing, you know, we're obviously competing just across all of STEM (science, technology, engineering, and mathematics) with other areas and other fields, and so fusion is very, very attractive, but there's lots of other fields that are very attractive, too, so more STEM is better across the board.

Internationally, the—we find the, you know, the Germans, the Italians, and the U.K., those programs are growing new facilities. And those new facilities are very attractive to bright researchers. And so we have to have those, you know, competing facilities in the United States if we want to attract them.

Dr. COWLEY. There's a very interesting development coming up very, very fast in fusion. And that came out of the German program. For a long time we've known that three-dimensional devices, which are—don't have an intrinsic symmetry, might make very good fusion reactors but they're very complicated. And it wasn't until we got supercomputers to optimize those configurations—and this happened in the German program—and start to use machine learning techniques to optimize the shape of the coils, et cetera, that we're getting machines that produce fusion-level performance. And the Wendelstein machine, which is on the Baltic coast of Germany, has been producing fusion-level performance in one of these three-dimensional machines.

And now we're starting to have to compete with, you know, the tech companies for their machine learning experts and, you know, their computer programming experts and stuff. I'm very excited by this because this is just almost pure thought happening. And we have a collaboration with the Simons Institute and the Simons Fund in New York to develop some of these ideas about optimizing three-dimensional machines that might make the best option for the future in fusion.

Mr. MEIJER. Well, thank you. And my time's expired, but I share the excitement over that multidisciplinary possibilities between the additive manufacturing, machine learning, fusion technology. The way that all of that is coming together is truly exciting.

And with that, Mr. Chairman, I yield back.

STAFF. Ms. Bonamici is recognized.

Ms. BONAMICI. Thank you so much to the Chair and Ranking Member and to our impressive panel. I very much appreciate this discussion that we're having about the need for a skilled work force both as we rebuild infrastructure but also as we transition to a clean energy economy. And it's something that I work on frequently as a Member of the Committee on Education and the Workforce.

And, Dr. Cowley, thank you for mentioning apprenticeship. It happens to be National Apprenticeship Week. But it really is a key to—you know, as we're looking at these policies and going forward, we need to have people with the skills to do the work.

And so, Dr. Mumgaard, in your testimony you reference the growth of the renewable energy sector over the past decade and how in 2019 renewable energy consumption surpassed coal for the first time in more than 100 years. But how does the development of fusion energy compare with that sort of advent and the proliferation of other zero-carbon technologies like solar and wind, and what can we learn from the U.S. Government's efforts to support wind and solar? And how can we apply those lessons in fusion?

Dr. MUMGAARD. Yes, it's been very interesting to watch fusion, you know, at this very early stage execute what looks like a traditional scaleup the way we saw wind and solar, the way that we've seen nuclear back in the 1950's, and the way that we see other technologies outside of energy where you start with a few, you know, few people that are pathfinding based on the basic science that then sort of pick up momentum, and the more people join the field. They join at all different stages of their careers. And hopefully we could get enough foresight to be able to build the programs that are going to train the next generation of people that we're going to need.

And if you look at renewables in particular, you know, renewables had to train everyone from the people that maintain wind turbines to the people that manufacture solar panels to the people that figure out where is the best place to build one and where is the best place to hook it up to the grid. And so you have to think holistically about that whole chain of going from the—you know, not just the science but also the feedstock materials all the way to the point of operating, repairing, and interconnecting those machines.

And I think fusion has a big advantage. So, one, it looks a lot like the energy sources that have been done before in terms that it's a power plant that you go out and you build. In fact, you could even think about repowering coal power plants——

Ms. BONAMICI. Right, right.

Dr. MUMGAARD [continuing]. And that would have a lot of the same people involved, a lot of the same skills. And so we can possibly do this quicker than what renewables did because it's a less drastic change and because renewables have paved such a good roadway for us.

Ms. BONAMICI. That's really helpful. Thank you so much.

So, Dr. Cowley, you, I know, have overseen fusion efforts in the U.K. and now in the U.S., thank you for your work at the Princeton Plasma Physics Lab. So how do the efforts in the United States on fusion energy compare to the U.K.'s efforts, and what should this Committee consider when we're crafting policies to help promote U.S. leadership in fusion?

Dr. COWLEY. For many, many years the United States has been focused on just the science of fusion. And in that it's been enormously successful. The ability now to actually calculate what goes on in the science and the understanding, and the DOE's Office of Science has done a wonderful job in doing that. But it has remained divorced from the idea of actually producing an energy source, and that was never true in any of the European programs. It—and certainly not true in the Chinese program. The Chinese program is—has got their plan and they're going to deliver on it. It's a very conservative plan actually with not much risk in it. But the U.S. program has developed the science for the world, right, and it's been—that—I came here to graduate school and went back to the U.K., and we've all learned from the U.S. program. But it's curious in that the U.S. program has had as its goal fusion science, not fusion energy.

Ms. BONAMICI. And are you seeing a shift? And if so, is it enough of a shift to have that—the focus beyond fusion energy, not just fusion science?

Dr. COWLEY. I think the United States is uniquely capable of doing this. I mean, NE, the Nuclear Energy part of DOE, is a good place to start drawing resources from to be able to design and construct a program that'll go for energy. And I think what you've seen from the FESAC plan is that people want to do that. And we have the industrial base in order to do that. It's—you know, the—we're working, for instance, with a wonderful engineering company called Holtec out of Camden, New Jersey, and out of Pittsburgh on constructing pieces for this. It's precision engineering the United States can really do. I don't see any reason why the United States couldn't vault into the lead in a very short amount of time.

Ms. BONAMICI. That's very encouraging, and of course PPPL and our national labs I expect will be playing a significant role in bringing this transformative technology to market.

And it looks at my time is expired. I yield back. Thank you, Mr. Chairman.

STAFF. Mr. Gimenez is recognized.

Mr. GIMENEZ. Thank you, Mr. Chairman. From some of the things I've read about fusion technology, the problem seems to be the containment vessel, you know, itself. And I think we spoke about it a little bit. And, Dr. McCarthy, could you talk about that little bit more, the containment vessel, the destructive aspects of the fusion reaction itself on the vessel that's trying to—you know, that's trying to contain it? That seems to be the big issue with fusion reactors. And how close are we to finding some kind of solution to that?

Dr. MCCARTHY. So I think that's certainly one of the important issues. I talked about what we call the first wall. That is the wall that faces the plasma. It sees the high heat flux. It sees the neutron flux. And developing materials to withstand that are extremely important, and that's why we need, for example, a prototypic neutron source. But the other piece that we need—and it's tied to that but it's not—well, it's tied to it but a little different—is that whole blanket technology. How do we take the energy that comes out of the plasma, turn it into usable electricity, for example, or processing if that's what you want to use it for, in an efficient way? And you also have to produce fuel so that it's self-sustaining in terms of the fuel cycle. So it's a bit bigger than just that first wall.

The other thing we have to look at is the neutron flux on magnets, on superconducting magnets. That has an impact on their performance. So there's a large set of things that have to be looked at. But I would say that a lot of those tie to materials, and then that goes back to what Dr. Cowley was talking about and actually several people here on the panel in terms of the need to invest in materials that will perform over long periods of time.

Mr. GIMENEZ. Well, I mean, if you don't have a containment vessel that actually can contain the reaction, everything else is moot, right?

Dr. MCCARTHY. Yes, but so within the—in a fusion machine, we're actually using the magnetic fields to contain the plasma and keep it away from that first wall, but you still do get particles, you get heat flux that the first wall sees. So it's not exactly the idea of containment like you see in a fission reactor, right?

Mr. GIMENEZ. And you haven't solved that problem yet?

Dr. MCCARTHY. We don't yet have materials that would work in a commercial plant that would have—that would be able to sustain that environment—perform in that environment for long enough periods of time, but there's a lot of good work that's going toward that.

Dr. COWLEY. I would actually——

Mr. GIMENEZ. Are there fuels that will—are there fuels that are better than others in order to—in other words, that they don't emit the same kind of harmful radiation and destructive radiation that for materials—is there some kind of fuel that we'd be looking for that could do that, so a combination of fuel and materials?

Dr. MCCARTHY. Yes, so there are other potential fuels. Deuterium-tritium is considered the easiest because it requires the lowest temperatures, still temperatures about an order of magnitude hotter than the center of the sun. Other reactions, for example, deuterium-deuterium produce much fewer neutrons. They require higher temperatures in terms of heating the plasma. So what I would say is that when you look at fusion, the different configuration options, the different fuels, there's—none of them is the silver bullet that everything is easier. And what we have to understand is what are the tradeoffs? What are the problems that we can solve? And that takes you down a path of do you go for something that requires higher temperatures? Do you go for something that requires these materials? And that's where these technology roadmaps that we talked about earlier are important.

Dr. COWLEY. Can I just raise something? Because I think there's a slight misconception here. We do have materials that we think will probably work in a fusion reactor. The question is the lifetime of the wall, right?

Dr. MCCARTHY. That's right.

Dr. COWLEY. The lifetime will be long enough. We do have materials, but we've never tested them, so we don't know that for sure. And taking the risk of pushing them in a future fusion reactor before we've ever tested them doesn't sound like a very pragmatic thing to do. So it's not like we don't have a solution to this problem. We think we do, but we need to test it.

Mr. GIMENEZ. What do you need from us in order to make that happen?

Dr. COWLEY. I think the first thing is that—what they call a prototypical neutron source, right, and actually make some neutrons that are like the fission neutrons. When that neutron hits a steel—you know, an iron nucleus inside the thing, the iron nucleus recoils and it makes a little melt spot in the steel. And the important thing is you get steels that when they resolidify after that little melt spot, all the atoms go back into the right place. And we think we have steels that do that, but we have to demonstrate that we do.

Mr. GIMENEZ. My time is up. Thank you so much, and I yield my time back. Thank you, I appreciate it.

STAFF. Ms. Ross is recognized.

Ms. ROSS. Thank you very much, and thank you very much to Chairman Bowman for holding this important meeting. And I want to thank all the panelists for joining us today.

As we all know, climate change is an immediate and existential threat, particularly in coastal States like North Carolina (NC), and that's where I represent. That's why I've consistently supported investments in clean energy like wind and solar. But of course there are amazing potential out there in emerging clean energy technology like fusion, which is not intermittent and can serve as that kind of baseload potential and be good for the environment and for the future of our energy establishment here in the United States.

And the development that we've seen and that you've told us about have been remarkable. But the long-term success is going to be dependent on a robust cooperation among government, the private sector, and academia. And I represent NC State University, which is an engineering and STEM university in North Carolina.

And so, Dr. Carter, NC State's nuclear engineering department is the only nuclear engineering department in North Carolina and a premier department in the country. And the fusion energy industry can only be successful if we maintain a pipeline of graduates equipped to work in this field. And so I have questions about whether or not our U.S. universities are prepared to meet the labor demands in fusion energy and whether you have any suggestions for what our universities can do to ramp up.

Dr. CARTER. Thanks for that question. First of all, I'm a product of NC State University, so I——

Ms. ROSS. Yay.

Dr. CARTER [continuing]. Grew up in North Carolina. I'm very glad to hear you bring that up. Yes, I mean, as we've already brought up, we—you—the universities are seeing an influx of students at the undergraduate level, the graduate level that are really interested in fusion energy, more than we can handle. What we need to do is to strengthen the programs across the board in fusion energy, and this can be—this needs action at the university level. It needs action at DOE level to make it happen. We need programs that stimulate this. We need to give leadership opportunities to universities to lead programs. You heard about FRIB earlier. And these kind of programs where the universities really get visibility and leadership draws new faculty and resources from the university. So finding ways to do that I think is very important. We stand ready to do that. The universities that participate in this planning process are ready to roll up our sleeves and get to work. We could use some help, though, from the Federal Government and from other university systems to push for this change.

Ms. ROSS. All right. Does anybody else have anything to add before I ask my next question? OK.

So my next question is related to the infrastructure law that we just had the President sign this week. And we are going to be updating our electric grid, and we've—we're doing it because of storm damage, we're doing it because we want to put more renewable energy on the grid, and we've seen difficulties with getting that energy on the grid. Are there changes to our electric grid that we are going to need for fusion energy? And how can we prepare for that now?

Dr. MUMGAARD. Yes, so we've looked at that pretty extensively, and we have—CFS has investors who are in the energy industry. And one of the big advantages is that the fusion product—and independent of how we get there and what the configuration looks like, the fusion product is a very, very flexible energy source. And it comes in a unit size that's about the right unit size for the way that we build grids worldwide. So it's not too big, but it's also not so small. And you can turn it on, you can turn it off. There's—the things inside the actual plant don't really care that much about their history. And so that means that, you know, independent of how we do the electrical grid, we're going to have a spot for fusion in it, whether that is repowering existing sites that interconnect or even building out new infrastructure or new grids to support electrification. You know, fusion is a broad-based support for that.

Ms. ROSS. Well, great. Thank you very much, and I yield back.

STAFF. Mr. Obernolte is recognized.

Mr. OBERNOLTE. Thank you very much, Mr. Chairman, and thank you to our witnesses. This has been an incredibly fascinating hearing.

My first question is for Dr. Ma. I'd like to continue a line of questioning that Congressman Garcia had started. Congratulations on your achievement in August there at the NIF. That's an amazing breakthrough. You were testifying about the fact that—in response to Congressman Garcia's question, the fact that you've achieved about 70 percent of the energy input in terms of output from the fusion reaction. And he was asking about the pathway to get to breakeven, which, you know, as we all know is really what's going to be required for power generation. Also, as I understand it, you—we're not yet at a level where that reaction is self-sustaining. So I wonder if you could talk a little bit more about the pathway from what you've achieved in August to getting to something that's both exceeding breakeven and self-sustaining.

Dr. MA. Yes, thank you. And, first of all, let me acknowledge the enormous team that made this result happen and the decades of giants on whose shoulders we stand on and all of your support over the years.

Well, first of all, the NIF is a scientific demonstration facility for high yield, and it was never meant to be energy production. And so even when we achieve gain on the NIF, it does not mean there's—there will be enough energy coming out that you could economically run a power system. What needs to happen is a coordinated inertial fusion energy program in the United States, which does not exist right now, a program that could bring together the best minds and develop the technologies that need to occur to make IFE happen. And some of those technologies include drivers, i.e., lasers or pulse power or heavy ions that are economical. We need targets that can be built robustly and cheaply and mass-produced. We also need a better understanding of the overall physics. So all of those things need to come together.

In terms of what our next steps can be as a country now, we need to develop that framework for an inertial fusion program and figure out how we can also best leverage public-private partnerships. We need to develop a roadmap that is credible and feasible and pulls in our latest understanding with emerging technologies. And then we need to explore alternative schemes as well. There are very innovative ideas out there that could get us to those very high gains that we might need to build a power plant.

Mr. OBERNOLTE. Well, great, thank you very much. That's very helpful. We hope to work with you to achieve those goals.

My next question is for Dr. McCarthy. You were talking about the path to commercial fusion powered energy generation in the United States. And one of the things I—that you said that I thought was very pertinent was you were talking about the lower failure modes that we have in fusion energy production than we have in fission energy production. And I think that that's going to be critical because we have kind of a political problem with nuclear energy in general where some of the failures of the past are coloring public perception of fusion energy in the future. And so I wonder if you could talk a little bit more about those failure modes and about how once a reactor is self-sustaining, how a fission reactor has lower failure modes than a—I'm sorry, a fusion reactor has lower failure modes than a fission reactor because I think that that articulation is going to be very critical to gaining the widespread public acceptance that we're going to need to make this technology feasible.

Dr. MCCARTHY. So, first of all, I'll start out by saying fission reactors are safe. They are highly regulated. They have all those systems in place so that—to mitigate any abnormal events.

Now, if we look at a fusion reactor, there are some inherent differences. And one of them that I talked about has to do with the radioactive waste that's produced. So there are technical solutions to isolation of radioactive waste. They're—politically, they've not been successful, so we haven't moved forward really with long-term disposal for fission waste. We don't have the same issues with fusion because we don't have that waste that requires long-term geologic isolation. That's a big one from the perspective of public perception.

And then with respect to safety, what we in the industry call the source term, that's the stuff that could potentially be mobilized and scattered, the source term in a fusion reactor is much, much, much smaller than what's in a fission reactor. And what you have to look at is the combination of source term plus energy to disperse it. That's kind of how you look at safety from the big picture. So fusion has some advantages from that perspective.

But there's a lot that we can learn from fission and a lot that is applicable from fission to fusion when it comes to how we do things. Keeping things simple is very important. Fission is a relatively simple technology. This is one of the fusion challenges. So where we can simplify things and where we can—and I think it was Dr. Mumgaard who talked about how important it is to have the industry connection as we're doing this to understand what they want. That's one of the things we did in the National Academies report. The scientist's dream is not necessarily the utility's dream, and so that connection is important. And I apologize. I think I've gone over.

Mr. OBERNOLTE. Great. Well, thank you very much. We look forward to working with you to further the public perception there.

Mr. Chair, I yield back.

STAFF. Ms. Lofgren is recognized.

Ms. LOFGREN. Thank you very much, Mr. Chairman. I just want to thank you and Chairwoman Johnson, the Ranking Members for this important hearing today. And I wanted to extend a special welcome and thanks to Dr. Ma for being with us and for the work that she has done in representing the other scientists who worked over these many years at the National Ignition Facility.

You know, I was there—this has been a bipartisan effort. I was—I remember former Congressman Bill Baker leading the charge. I didn't agree with Bill on a lot of things, but we agreed on this. And then Ellen Tauscher, who took up the cudgel and generations of fighting for this. I remember when Ed Moses was the Director of the lab, and I asked him how will we know when we get burning plasma, and he said, well, you'll see the scientists doing handstands. So I was really pleased to be advised of the handstands right after August 8th by the Director of the lab, and I—it's a marvelous achievement and I appreciate it greatly.

You know, the NIF has played an important role, but you're—as you've mentioned, you're the science piece. You're not going to be the energy production piece. But you've got some more things to do. And so here's a question—a direct question—you don't need to agree with me because—or I know it's true. There have been fights with NNSA over the years about the NIF's science experiments versus the nuclear stockpile mission, which is a primary mission. I don't want—I mean, there were those over the years who thought that you could do science on a schedule, you know, and you can't. But you have achieved what we—I thought would be happening in a few years when I was at the groundbreaking and then the opening of the facility. You've achieved the burning plasma now. I want to make sure that you are getting what you need from NNSA in terms of the capacity to proceed on the further experiments because obviously we need the stockpile. Maintenance is a very important element of our security posture.

But our security posture is also dependent on limitless clean energy. We need to be able to remove carbon from the atmosphere because of climate change. We're going to need to do desalination, which is going to require a limitless pollution-free energy source because of the droughts that we are having in the West. So fusion is an essential element of our national security.

So are you able to say what you would need by way of support from your governing agency NNSA in order to optimize the science that still needs to go on at the NIF?

Dr. MA. So thank you for your comments and your continued support over the years. The NNSA has been a very good sponsor for us, and I think on the NIF we have demonstrated the success of the science-based Stockpile Stewardship Program. Very recently, we've done experiments on plutonium aging that have been very important for the NNSA mission, equation of State experiments, et cetera.

You are completely hitting the nail on the head to say that energy security and energy sovereignty are an important part of national security. And, as such, NNSA would—and they recognize that energy security is an important part of that. We are very focused right now of course on meeting certain milestones, and we're under pressure, so that is understandable. What would be very important for us is sustained and robust funding to ensure that we can continue to have strong scientific experiments on the NIF, to have a robust what we call discovery science program where we open up the facility to academics——

Ms. LOFGREN. Right.

Dr. MA [continuing]. Worldwide, and a little bit of flexibility to see the dual use purposes of the inertial confinement fusion research that we do on the NIF.

Ms. LOFGREN. Well, I thank you very much for that very skillful and diplomatic answer, and I look forward to—you know, there was a time when NNSA wanted to shut down all of the science projects a few decades ago, and the Congress rallied around in a day to put a stop to that. So I'm sure that we will have a bipartisan effort to make sure that the science gets done.

Let me yield back with thanks to Dr. Foster for letting me jump ahead of him.

STAFF. Dr. Foster is recognized.

Mr. FOSTER. Hello. Am I audible and visible here?

STAFF. Yes.

Mr. FOSTER. Great. Well, first, I'd like to echo my appreciation to the Chairwoman and Ranking Member for their work on the *DOE Science for the Future Act* and specifically to the Ranking Member for his polite restraint in his description of the Senate counterproposal, and to the scientific community for their enthusiastic embrace of the House proposal.

Now, Dr. Ma—well, first off, congratulations to you and the whole NIF team. You know, I understand there was a fairly celebratory mood at the DPP (Division of Plasma Physics) plasma physics meeting in Pittsburgh earlier this month, and so say hi to everyone that I know there, some mutual friends.

You know, one of my pet peeves when I was a practicing scientist was congressional micromanaging of science, and so now hereby I get my revenge. Now, I understand that following your record-breaking 1.3 megajoule shot, there have been a couple of subsequent shots with more yields in the range of a half a megajoule, so what is the current best understanding of what's going to be required first for reproducible yields and eventually further yield improvements? You know, is there sort of a detailed roadmap or a flowchart of future shots that might be provided to us to track progress against?

Dr. MA. Absolutely, yes. So we—like you said, we have recently done a few repeat shots, and we did our best to try to replicate the target, the laser performance, et cetera. However, we know that when we built the NIF with the 1.92 megajoules of laser energy that the laser has, we were just right at the hairy edge of what we would need for ignition. So every little detail counts here. Every bump, every dip, every speck of dust. Oh, I take that back. We don't even have specks of dust on our targets. But they all play a role in the physics performance that we see.

So with those repeat shots, we—the yields were a little bit lower, and that is because there were some more imperfections in the target. The laser delivery was not quite as good. And we're now doing the analyses, and we will go through the scientific peer-review process to ensure the community agrees with us. But we are trying to understand those sensitivities of those different parameters.

Now, going forward, we will continue to test by pushing to slightly higher velocities, which for us equates to kinetic energy into the system. And we are testing slightly different target designs that should give us a little bit higher coupling. And those experiments will take several years to do. Because our experiments are so complex, each one takes several months to actually set up. So stay tuned, but that's what the roadmap looks like going forward.

Mr. FOSTER. OK. You also mentioned that heavy ion accelerators as a potential energy efficient fusion driver at least for the compression maybe to follow with fast ignition or something like that. You know, as you may know, I served on the DOE Heavy Ion Fusion Advisory Board back in the day. And so is this an effort that's likely to be reenergized following the NIF yields?

Dr. MA. We will certainly be looking into heavy ion fusion. The advantage of heavy ion fusion is you can get much higher coupling efficiencies of driver energies into the targets.

Mr. FOSTER. Yes.

Dr. MA. The heavy ion fusion program was shut down in the mid-2010's because it was recognized that to do those experiments you really have to do them at scale. And you need very——

Mr. FOSTER. Oh, yes. No, I'm aware of the challenges. I was just wondering if that's something that people are going to—you know, and there was a rather demoralizing decade for inertial fusion generally because of the frustration over NIF that has now evaporated.

Also at about a decade ago Livermore and the ICF community put a lot of effort into what was called the LIFE (Laser Inertial Fusion Energy) project. And this is a fusion-fission hybrid which uses the fusion base there as a source of neutrons and the energy produced mainly in a fissile blanket around it. And potentially that can be used to burn spent nuclear fuel, burn excess weapons-grade plutonium, all sorts of other side benefits. Is this an effort that's also maybe worth reviving now that you're getting the yields that you planned to a decade ago?

Dr. MA. So, as a community, we absolutely hope to build off the good technical work that was done on LIFE, which was a full systems engineering and looking at all the different components. However, that is a decision that will need to be made by DOE, and we will also be holding a basic research needs for IFE in the next year where we will lay out what the priority research directions are. And I expect that continuation of the LIFE work will be a component of that.

Mr. FOSTER. OK. And now I have used up all my time and maybe 1 percent of the questions I have. Congratulations to everyone.

STAFF. Mr. Beyer is recognized.

Mr. BEYER. Thank you very much. And Chairman Bowman, thanks very much for holding this hearing. This is the most exciting hearing I've seen in 2021 in terms of the potential.

I keep talking about, you know, we have a little more than $1 billion for fusion energy coming out of a—blessed by the Science Committee and included in *Build Back Better,* and in a bill that could be approaching $2 trillion, this is the stuff that's most transformational, so I'm really excited that you guys are leading on this.

Dr. Ma, you talked again and again about inertial fusion energy. Is that a different idea than what Dr. Mumgaard is doing at Commonwealth Fusion? Is this a different approach to fusion energy?

Dr. MA. Yes, it is. The idea behind inertial fusion is you use the inertia of the target itself to do the compression and holding together the plasma long enough for fusion reactions to occur. With magnetic fusion, you use magnetic fields on a much lower density plasma to hold that together for actually longer amounts of time to get that to fuse.

There are pros and cons and advantages to both schemes. With inertial confinement, one of the major advantages is that you get to actually separate the target from the driver itself, so it—whether it's lasers, pulse power, heavy ions, you can deliver that laser energy separately from the target design. And so you—it allows for flexibility in how you test out those two schemes.

There are a lot of overlaps in terms of reactor building, the materials challenges that we would have, so we do hope to work together and learn from each other.

Mr. BEYER. Thank you. Sir Dr. Cowley, you know, you talked a little bit about the National Academies survey, and—which is pretty optimistic, not as optimistic as the private sector is, Commonwealth Fusion and Helion and others. Are there specific—is it possible to lay out the series of specific benchmarks in technology and science that have to be met in order to get to commercially available fusion?

Dr. COWLEY. Well, first, you fought a war so that you didn't have to call me sir.

Mr. BEYER. It's still pretty cool.

Dr. COWLEY. Yes, that's actually one of the things that I think we need to really settle in and do after the FESAC plan, which is a technology roadmap, the kind of technology roadmap that tech companies put forward when they want a new product or a chip company puts forward when it wants a new product because there are lots of little details that could fall through the cracks and then delay, you know, the delivery process. So the idea of having fusion pilot plant designs done in this next—really, we should get started today—is that, as we get those designs, we can work back from them and say we need to solve this problem by, you know, 2022, this problem by 2024, you know, and that kind of technology roadmap. So it's critical at the moment, yes.

Mr. BEYER. Thank you very much.

Dr. Mumgaard, I've been telling everybody that, you know, the old DOE was 2060, and then the Academies move it up to 2040, and you guys are saying maybe 2030. Can I say that with credibility?

Dr. MUMGAARD. So, you know, the survey of all the fusion companies says—the majority say 2030's. And why do we think that's possible? We think that's possible because it's a confluence of various technologies that are all happening at once plus the capital and sort of human infrastructure both on the stakeholder side and simply on the employees' and engineers' side that allows us to try things. So, you know, for instance, when we went to the National Academies in 2018 and said we want to develop a high temperature superconducting magnet, you know, the view was maybe that would take 10, 20 years and we did it in 3, and we were able to do that not because we're smarter than everybody or anything like that, but we are able to do that because we can apply lessons learned in how you do really fast iteration of build, try, break, build, try, break very, very quickly. And some parts of fusion are conducive to that where you don't necessarily need a centralized plan that's very, very serial. You can break it into modular pieces that you can try out, break, and integrate only when you absolutely need to do that.

And so if you look across the companies, that's a defining factor of many of them is how do you make problems into things that you can separate? How do you make problems into things you can try? How do you get iteration into the loop? And then how do you couple that with people that are very, very good at building things very, very quickly?

And so, you know, we think that it is feasible to get these types of systems online in the '30's. And perhaps more importantly, the timeline is, you know, set by the climate and by the energy transition, so there is a huge amount of pull to go faster. You know, if we all got to choose what is the path to get there and what is the right time to get there, we make different choices than what carbon is choosing to force us to do. And so that impacts, you know, our planet, CFS every single day, that timeline, how do we make technical decisions that could enable that timeline. And it's really a good thing for this Committee today because, you know, we're talking about what are the investments we need to make now that would give us a better shot at that, not just CFS but also the pilot program and also the other companies.

Mr. BEYER. Well, thank you. Yes, I get discouraged by how slowly we move here, so my new legislative strategy is build, try, break.

Chairman BOWMAN. Well, once again, thank you to all of our witnesses for being here. This was an amazing hearing about a topic that, you know, I think will take our economy and humanity into the future, so this is really exciting.

The record will remain open for 2 weeks for additional statements from the Members and for any additional questions the Committee may ask of the witnesses. The witnesses are now excused. The hearing is now adjourned. Thank you again so much.

[Whereupon, at 12:20 p.m., the Subcommittee was adjourned.]

Appendix

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Robert Mumgaard

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Fostering a New Era of Fusion Energy Research and Technology Development"

Responses to Questions for the Record to:
Dr. Bob Mumgaard, CEO
Commonwealth Fusion Systems
Submitted by Representative Jerry McNerney

1. In your testimony, you discussed how despite historical leadership in fusion research and development, the U.S. risks permanently falling behind other nations.

> a. Can you elaborate on these risks—financial or otherwise—that could hinder U.S. leadership, and what steps the government should take to ensure the domestic industry remains competitive?

The fundamental way we approach fusion research and development in the United States puts us at risk of permanently falling behind other nations. Today, the Fusion Energy Sciences (FES) program sits within the Office of Science at the Department of Energy (DOE). FES is a science-based, not energy-based program with two primary goals to 1) expand the understanding of matter at very high temperatures and densities and 2) build the knowledge needed to develop a fusion energy source. This focus is outdated and no longer aligned with the progress that is being made in the private sector on developing commercial fusion energy systems.

There are a number of recent reports that provide a roadmap for advancing U.S. interests in fusion energy, including the December 2020 DOE Fusion Energy Science Advisory Committee (FESAC) Long Range Planning subcommittee report "Powering the Future Fusion & Plasmas" and the March 2021 National Academies of Science (NAS) report "Bringing Fusion to the U.S. Grid". Both reports advocate for refocusing our national effort towards a commercial fusion energy mission and utilizing public-private partnerships to accelerate the deployment of economical fusion energy. The reports also identify critical areas of research and a prioritization of investments to maximize impacts. To date, there have been no announced plans to implement the recommendations of these reports.

The U.S. is not making the necessary investments in new facilities that would support a commercial fusion energy mission. In addition, current government funded programs continue to suffer from schedule delays and cost overruns, most notably in the National Spherical Torus Experiment-Upgrade (NSTX-U), and International Thermonuclear Experimental Reactor (ITER) efforts. It is not clear to industry where the U.S. fusion program is headed, making it difficult to assess its future and the possibility of future collaborations.

Other countries are not waiting in their pursuit to harness the power of fusion energy. They have made clear their intentions to develop and commercialize fusion energy and are taking definitive steps to do so. The United Kingdom and China have made explicit statements to be the first to commercialize fusion and respectively have put hundreds of millions of dollars into their programs, including private public partnerships. The U.S. has not.

One of the most immediate actions that can be done is for DOE to implement the programs that have already been established by the Energy Policy Act of 2020. The Act was the most comprehensive update to the nation's energy policies in over a decade. It sets priorities for research, development, and demonstration of a range of technologies at DOE including renewables, nuclear, energy efficiency, grid modernization, energy storage, carbon capture utilization and storage, manufacturing technologies, and critical minerals, as well as energy tax credits. Furthermore, the Act established two key public-private partnerships (PPP), the Innovation Network for Fusion Energy (INFUSE) and the milestone-based Fusion Development Program. While DOE has implemented the INFUSE program, it is not nearly at the level that it needs to be to have an impact in accelerating bringing fusion power to the grid. It represents approximately 1% of the FES budget of approximately $670 million. And we still do not have the funding or seen steps by FES to implement the milestone-based PPP program. This program has been modeled after the successful National Aeronautics and Space Administration (NASA) Commercial Orbital Transportation System (COTS). It represents a new and improved way of conducting PPPs for DOE and would align the public programs with the planned private sector led pilot plants, such that industry accepts a major portion of the risks by simply agreeing to meet their agreed-upon milestones. If they don't meet those milestones, then no government funds are issued for reimbursement.

Combining the speed and agility of the private sector with government support and programs is not a novel concept. For example, levering the COTS model, SpaceX has positioned the U.S. as global leader in space. In recent remarks, the President's Science Advisor and Director of Office of Science and Technology Policy at the White House, Dr. Eric Lander, said "the race is on" to commercialize fusion energy. An alignment between private sector and public sector fusion initiatives is needed if the U.S. is to win the race to commercialize fusion energy.

For the U.S. to win "the race", we will need to achieve the stated goal of leading the world in creating a domestic fusion energy industry. The DOE will need to invest in the facilities highlighted in the DOE FESAC and NAS reports. The need to invest was made a requirement by the House passed version of the "Department of Energy Science for the Future Act" in which the FES Director is required to factor both reports into the future planning process of the Department. The U.S. fusion energy mission should be supported by rigorous programs at public research institutions. These actions should be taken in a timely manner utilizing any, and all flexibilities in the procurement process including utilization of the department's other transaction authority and consideration should be given to locating the milestone-based program outside of the Office of Science. Congress has recognized the need to locate other demonstration programs outside of the DOE program offices by creating the Office of Clean

Energy Demonstrations. ARPA-E has also shown a unique capability of working with industry and should be considered as a possible location or facilitator of the program.

The private sector has demonstrated they are in the race. There are now over 35 private fusion companies and in the past two months the industry has gone from $1.8 billion in invested capital to over $4.1 billion. Now is the time for the U.S. to prioritize being first to commercial fusion and provide the partnership and support for the first commercial fusion power plant to be built here.

2. Commonwealth Fusion Systems has set ambitious time and cost goals for building an operational fusion power plant. How was your company able to achieve these milestones at such an accelerated pace and could your success be used as a roadmap for others?

At CFS our mission is clear, we intend to pursue the fastest path to commercial fusion energy by combining proven science with revolutionary magnet technology that can meet growing energy demands and combat climate change in timescale that matters. There are several factors that give us confidence we can build a smaller, faster and commercially relevant fusion machine. First, a new high temperature superconductor (HTS) recently reached industrial maturity and using HTS, CFS has built and demonstrated a first-of-a-kind high field superconducting magnet. These new HTS magnets will enable CFS to build a much smaller and commercially relevant tokamak that can achieve net energy from fusion at 1/40th the size in volume of ITER, the multinational tokamak machine being built in France. Second, we are using proven science with decades of research having established the tokamak-based configuration being used by CFS as a leading approach to confining fusion-grade plasmas with strong magnetic fields. Additionally, the ability of CFS to leverage commercial supply chains for our fusion devices translates to a faster path for building a fusion pilot plant in the early 2030s and is paving the way for to deliver wide-scale deployment of fusion energy power plants in the future. Our design and material choices also mean we should not be limited by access to special or limited source materials as the industry reaches scale.

We have also built a high caliber, diverse team drawing talent from leading organizations, including proven tough tech companies. This enables us to pursue a development model similar to other highly successful start-up companies. We take risks and iterate quickly using our learnings. We take these risks not simply for the sake of risk taking and not being afraid of failure, but because using a build, test, learn model translates to faster and cheaper development. An analogy would be SpaceX's development of Falcon launch system and the Dragon spacecraft systems. They leveraged the speed and agility that comes with commercialization in a unique public-private partnership arrangement with NASA through the Commercial Orbital Transportation System (COTS) program. Over the life of the program, SpaceX was able to iterate their designs and test to failure with rockets blowing up to learn very quickly, while achieving significant savings compared to a traditional NASA approach. SpaceX was able to develop a launch vehicle (Space Shuttle replacement) at 10 times less than the traditional NASA cost-plus approach for space vehicle development with 2.5 times less than traditional NASA management costs and 2-3 times less than the operational recurring costs per kilogram of cargo delivered to the International Space Station under a scenario where the Space Shuttle would have continued fulfilling the cargo requirements.[1]

CFS recognizes the identified benefits of previous and future collaborations with DOE-sponsored and other research programs. Partnerships such as those with national laboratories and universities provide access to the deep understanding, institutional learnings, toolsets, and data that can accelerate development timelines. Implementing and funding the authorized fusion energy cost-share, milestone based public private partnership, similar to the COTS program, will mean that timelines and costs for fusion energy can also benefit from combining the speed and agility of the private sector with public sector resources of technical expertise, research and testing facilities, and funding. However, this will require alignment of the public sector to the private sector priorities and timeline, examples include realigning research priorities and access to testing facilities at the national labs. This is how the U.S. will win the race to bringing fusion energy to market.

CFS and its leadership fully understands that there is much work to be done. The challenges are complex, but we are committed to providing the country and the world with a new source of clean energy.

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[1] American Institute of Aeronautics and Astronautics, *An Assessment of Costs Improvements in the NASA COTS/CRS Program and Implications for Future of NASA Missions*, https://ntrs.nasa.gov/search.jsp?R=20170008895 2019-02-28T16:48:50+00:00Z

Responses by Dr. Steven Cowley

Responses to Questions for the Record to:
Dr. Steven Cowley, Director,
Princeton Plasma Physics Laboratory
Submitted by Representative Jerry McNerney

1. *Dr. Cowley, can you speak to how the National Labs have provided a unique structure to advance fusion energy research? Do these facilities need to be scaled up to meet the timelines and recommendations in the 2021 Fusion Energy Sciences Advisory Committee strategic plan?*

The National labs provide a unique set of capabilities to take fusion to commercial realization. Commercial realization will inevitably involve private enterprise – but those efforts will need the unique structure, infrastructure and skill base of the labs. In this discussion I will treat General Atomics as an equivalent National Lab in fusion. We note that:

i. Labs generate ideas: Achieving commercial fusion requires aggressive innovation and new ideas. All the important current or proposed fusion experiments, public or private, are an outgrowth of science largely developed at the labs;
ii. Labs conceive, design and construct facilities at scale: Fusion requires scale in dimension and energy; National labs provide the expertise to operate at scale;
iii. Labs perform the largest scale computing: Recent advances in predictive computer simulation of fusion systems (at both the labs and Universities) are extraordinary; Accelerating fusion will require harnessing innovation in the virtual world. Fortunately the U.S. National labs host, operate, and exploit the most advanced computers in the world;
iv. Labs operate nuclear facilities safely: Fusion requires both advanced radiation and electrical safety; this is routine in the National labs.

The community plan identified key facilities and programs that are needed to accelerate fusion. For example, a point high energy neutron source is needed to understand how fusion neutrons interact with materials. The National labs host and operate neutron sources and are thus ideal hosts for such a fusion neutron source. To meet the ambitious timeline proposed in the community plan and the National Academy report, the National lab fusion program must be significantly expanded to:

i. Drive fusion pilot plant design and co-design activities (with partners);
ii. Host a point neutron source;
iii. Advance the predictive computer simulation of fusion systems to allow optimization *in silico* and drive innovation through virtual prototyping;
iv. Support private industry with technical expertise and provide safe secure sites for private facilities;
v. Develop the technologies of power handling and tritium breeding blankets. Key facilities and test stands are needed to develop technologies to readiness levels where industry can adopt.

Bringing fusion to market requires an approach that exploits the combined strengths of universities, private industry, and National labs. With the expansion indicated above the National labs can deliver their component.

2. What are some of the methods under consideration to translate fusion energy reactions into electricity?

Fusion reactions produce energy in the form of the kinetic energy of neutrons and charged particles. In the easiest fusion reaction (the one between two isotopes of hydrogen deuterium and tritium) 4/5ths of energy is in a high energy neutron. Current schemes propose that this energy is converted into heat in a "blanket" surrounding the fusion chamber and that the heat be used to power a turbine to make electricity. Blanket technology is at low technology readiness levels. Other ITER partners, though not the U.S., will test blanket concepts on ITER at low-power levels. Expansion of research on blankets will be required to develop fusion power.

In more advanced fusion concepts using considerably harder fusion reactions (e.g. the reaction between hydrogen and boron), power might be extracted electromagnetically from the charged particles and converted to electricity directly. While these concepts are attractive, they are best described as preliminary at this time.