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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.