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*The Future of U.S. Fusion Energy Research*
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I would like to thank the Committee for this opportunity to share my views on the status and future prospects of the U.S. fusion program. I want to stress that these are my own views and do not necessarily reflect the views of my employer.

The U.S. and the world have made enormous progress toward achieving fusion energy, putting within our grasp major milestones that will demonstrate the feasibility of fusion energy. ITER construction for First Plasma is now over 50% complete and initial operation of the facility is planned for 2025, just seven years from now. In addition, ITER plans to begin an experimental campaign in 2035 that will demonstrate a 'burning plasma', a key moment in the realization of fusion energy wherein a self-heated plasma will for the first time be created, sustained, and studied. With these milestones clearly in view, the world's magnetic fusion program is now progressing rapidly toward a major inflection point for fusion energy development. However, despite this progress and opportunity, the U.S. fusion program is at significant risk of losing its position as a world leader as other nations are expanding funding on fusion development while U.S. funding is in decline.

I have been engaged in magnetic fusion energy research for the past 30 years, both in the national and international arenas. This involvement has given me a keen appreciation of the promise offered, the challenges involved, and the opportunities presented by developing fusion as an energy source for the future. From these experiences and perspectives, I offer the following for consideration by this Committee:

- Fusion energy has the potential to provide enormous amounts – more than 10,000 years from known land resources – of base-load electricity that is virtually free of greenhouse gases and available to all nations of the world. *The extent of fusion's potential is unmatched by any other known energy source and therefore worth sizeable investment toward its development.*
- Successfully delivering fusion energy demands integration of several high-tech elements that span a wide range of scientific and engineering disciplines. It is unlikely that the required breadth of R&D can be undertaken by a single corporate entity; hence, *government sponsorship in the near-to-intermediate term is required to promote R&D activities over the full range of capabilities required for fusion energy.*
- *The U.S. fusion community is passionate about making fusion energy a reality and is leading the world research program in several key scientific areas*. This exciting, world-class research, carried out on world-class facilities, continues to place the U.S. in a

leadership role in the development of fusion energy (though that leadership is threatened due to large investments by other nations).

- Looking forward, burning plasma research is an essential element in the development of fusion energy as future fusion systems will rely on the production and sustainment of such plasmas. ITER will provide this platform for U.S. researchers. As the only existing project worldwide intended to create a burning plasma at the scale of a power plant, I believe *it is critical that the U.S. remain a party to the ITER project and position itself to exploit ITER by maintaining and acquiring expertise in critical technical areas through research on existing facilities, theory, and simulation*.
- Beyond ITER, significant opportunities exist for U.S. leadership in fields that enable realization of fusion energy (e.g., fusion nuclear materials) and/or development of more cost-attractive approaches to fusion energy (e.g., innovative confinement concepts, high-critical-temperature superconducting magnets). To capitalize on these opportunities, *the U.S. needs a vibrant domestic research program that can, alongside ITER participation, deploy leadership-class facilities and capabilities in these key research areas.*
- Strategically, the U.S. path to fusion energy is unclear at the moment, especially with funding trending downward. This stands in contrast to other ITER partners that have developed strategic plans structured to capitalize on ITER success to aggressively pursue fusion energy development. Our country's lack of commitment toward pursuing fusion aggressively puts us at risk of falling behind in the quest for fusion energy. In this regard, *the U.S. government should develop a clear policy on the importance of fusion energy as a national strategic interest and the role of fusion energy in national energy plan.*

During the rest of this testimony, I would like to offer my personal perspectives on these considerations, drawing from my experiences in the field, followed by some recommendations for this Committee to consider in developing legislation in the future.

**Fusion Energy for the World's Future**

*The quest for fusion energy is here to stay.* Fusion energy, the same process that powers the stars, offers the potential of a very compelling energy solution for the future with a readily available fuel supply, no greenhouse gas production, and the ability to serve as a large base-load supplier of electricity. The fuel for future fusion systems is abundant with estimates projecting over 10,000 years of availability from known land sources and significantly more if ocean resources are utilized. Future fusion systems will produce virtually no greenhouse gases, have no risk of uncontrolled meltdowns, and can be tailored to minimize the production of very-long-lifetime radioactive materials. Because of its promise, fusion energy will always motivate pursuit of solutions even though the development of fusion energy presents many significant technical challenges.

The potential of fusion is evidenced by the recent surge in the number of private startups evaluating innovative approaches to fusion energy. While this surge is indicative of emerging interest, it should be noted that these startups are focused heavily on developing high-risk, high-reward approaches to producing and confining fusion-grade plasmas, and therefore still require comprehensive programs for developing the full range of capabilities needed for fusion energy production. ITER, on the other hand, seeks to create and sustain a burning plasma using the most mature confinement configuration and demonstrated technologies, positioning it as a lower risk approach to the study of burning plasma science.

The science and technology of fusion requires state-of-the-art capabilities in a wide range of disciplines (e.g., plasma physics, materials, magnets, fuel cycle). Because the required technical capabilities are beyond those needed for other applications, fusion R&D must confront these challenges itself. In contrast, owing to fusion's interdisciplinary nature, many different fields of study have benefitted from fusion research. Spinoff technologies from fusion investments have had a transformative effect on society, with the public benefitting greatly from areas such as modern electronics, lighting, communication, manufacturing, and transportation.[*]

U.S. universities, labs, and industry have distinct leadership capabilities in the areas listed above with world-class researchers tackling the most challenging issues. However, the U.S. is not alone in this pursuit, with other nations (particularly the ITER Members) aggressively pursuing development of new capabilities that will further these disciplines while advancing fusion energy towards its development goal.

A major consideration for the time scale of fusion energy development is the observation that many economic models indicate a significant expansion of the world's electricity requirements in the latter half of this century. This is especially true for under-developed and/or emerging economies in which energy supply will likely pace economic growth and the quality of life in those countries. Because of this increasing need for clean energy sources and the short time scale involved, the U.S. has a distinct strategic interest in remaining a leader in energy technologies such as fusion. To this end, the U.S. needs to prepare for this opportunity now, putting in place the necessary technical know-how to position the U.S. at the forefront of future fusion development worldwide.

**The U.S. Fusion Program**

*The U.S. program continues to be a world leader in the development of the scientific basis for fusion energy.* This leadership is evidenced by the fact that U.S. researchers have been recognized for the Nuclear Fusion Prize[†] in 8 of the 13 years of the award for most impactful article in Nuclear Fusion, the top journal for publications of fusion research. In recent years, experiments on Alcator C-Mod (at MIT) and DIII-D (at General Atomics), motivated by U.S. theoretical studies, achieved record levels of normalized fusion performance that offer the potential of significantly improved fusion systems in the future. DIII-D has demonstrated scenarios that achieve the required level of ITER normalized performance in ITER-prototypical conditions, further increasing confidence that ITER will succeed in its mission.

These experimental findings are bolstered by detailed simulations in which U.S. scientists have modeled how small-scale fluctuations transport energy from the hot core to the edge in ITER, providing a much stronger scientific basis for projecting ITER's fusion power production. Scientists have also utilized emerging supercomputing capabilities to model how turbulence is spontaneously suppressed in the edge of tokamak plasmas leading to a factor of two increase in confinement quality, potentially solving a long-standing mystery of the field. All of these results

[*] https://science.energy.gov/~/media/fes/pdf/program-documents/FES_Brochure_hires.pdf
[†] https://www-pub.iaea.org/books/iaeabooks/Nuclear_Fusion/NF/NFAward

were enabled through a vibrant partnership between national labs, universities, and industry. Separately and collaboratively, these groups have provided pioneering contributions in theory, high-end computing, sensors, magnet technology, and innovative concepts that have advanced our understanding of fusion plasmas and motivated exciting new approaches to achieving fusion energy sooner, rather than later.

This research has enabled the U.S. fusion program to be a world leader in informing the design and research plan of ITER. Looking forward, U.S. leadership in fusion is at risk due to a myriad of challenges including: 1) decreasing U.S. funding at the same time of increased investment in other countries; 2) the increasing scale (and therefore associated investment) of facilities required for fusion development; 3) maintaining university engagement as facilities increase in size and complexity; and 4) the lack of a coherent U.S. strategic plan that defines the technical objectives and associated deliverables for fusion energy development in the U.S. Some recommendations for addressing these issues are discussed later.

*General Atomics' role in this enterprise:* General Atomics (GA), as a leading industrial partner in the development of fusion energy in the U.S., is committed to the success of the U.S. fusion program and sees compelling opportunities for government-sponsored research to accelerate the path to fusion energy. General Atomics has been involved in fusion energy research for over 60 years. GA presently operates, for the Department of Energy, the largest magnetic fusion User Facility in the U.S. – DIII-D.[‡] DIII-D is a highly collaborative program powered by the contributions of research staff from 28 U.S. universities and 7 national labs as well as GA itself. This program supports over 600 scientific users from 20 countries and has provided numerous pioneering contributions to the technical basis for ITER.

GA is also building the ITER Central Solenoid magnet for the U.S. ITER Project Office as part of the U.S.'s in-kind contributions to ITER. This magnet will sit in the very core of ITER and produce the transformer action that generates 15 million amperes of plasma current in ITER. Because this plasma current is essential for producing the magnetic fields that keep the hot plasma away from the containment walls, the Central Solenoid is sometimes referred to as 'the heartbeat of ITER'.[§] The first of seven production coils – each 14 ft in diameter and 7 ft tall – is now 80% complete with present schedules calling for all seven to be completed by 2022. We hope Members of this Committee will be able to visit our facility in Poway, CA to see the stunning scale of this project and learn more about the ITER project. This broad experience in fusion development provides GA with a unique perspective on fusion activities

The first of seven magnets for ITER's Central Solenoid following heat treatment to create the solenoid's superconducting material.

[‡] https://science.energy.gov/fes/facilities/user-facilities/diii-d/ and https://www.youtube.com/watch?v=tA7J2s23lB8&feature=youtu.be

[§] http://www.newswise.com/doescience/?article_id=639890 within the U.S., both those pertaining to government-sponsored research and investment opportunities for industrial involvement in the fusion enterprise.

**U.S. participation in ITER**

ITER's mission is to demonstrate the scientific and technological feasibility of fusion energy.[**] This mission is sufficiently ambitious and compelling that seven Members (China, European Union, India, Japan, Korea, Russia, and the U.S.) are partnering together to design, construct, and operate this facility. This consortium represents over 50% of the world's population and over 80% of the world's gross domestic product. The U.S. derives multiple benefits from this partnership including: a) a stronger scientific basis for design and operation of the facility; b) significantly increased breadth of expertise, facilities, and tools; c) industrial fabrication capabilities developed overseas; and d) sharing of costs with the US paying only 9% of the construction cost.

ITER's primary technical goal is to produce plasmas that produce 10 times more fusion power than is being injected into the plasma from external means. <u>The plasmas in ITER will reach 150,000,000 °C, approaching 10 times the temperature of the core of the Sun.</u> At these temperatures, the plasma will enter a state in which the heating from the fusion-produced alpha particles will exceed the heating applied from external sources such that the plasma becomes highly dependent on its own self-organization processes and less on external control (a state known as the 'burning plasma' regime).

The recently released interim report[††] from the National Academies of Sciences, Engineering, and Medicine Committee on a Strategic Plan for U.S. Burning Plasma Research affirmed the importance of research in this regime and of ITER itself stating:

> "*Any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary for such an inherently large project. A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.*"

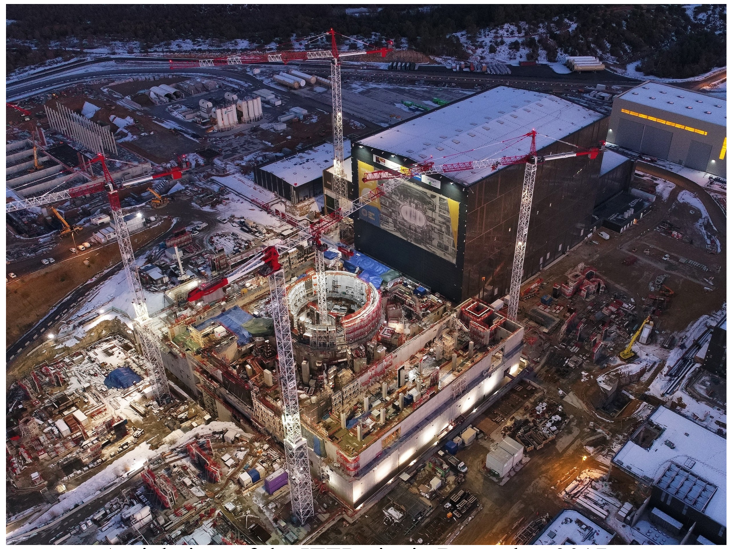
ITER is a highly leveraged investment for the U.S., requiring a 9% of cost investment in return for 100% of the technical information that will be learned from ITER, including the technical know-how developed in the other ITER parties. Over 80% of the U.S. funding is being used to fabricate components and establish technical expertise in the U.S., including the ITER Central Solenoid being built at General Atomics.

Following a management restructuring in 2015, ITER construction has accelerated with delivery

[**] https://www.usiter.org/fusion/U.S._ITER_Factsheet.pdf

[††] National Academies of Sciences, Engineering, and Medicine. 2017. Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research. Washington, DC: The National Academies Press. https://doi.org/10.17226/24971.

of several key components to the ITER site and construction advancing at a rapid pace. The most important action in this restructuring was the naming of a new Director General (Bernard Bigot) who in March of 2015 presented an action plan and was given the authority required to manage this project effectively. This restructuring has resulted in a better-equipped, more nimble organization capable of responding to emerging needs in a timely, effective manner. This is evidenced by the fact that, since 2015, project milestones have consistently been met on or ahead of schedule.[§§] This progress has taken the ITER project past the 50% completion mark for systems that are required for first plasma in 2025. For its part, the U.S. successfully delivered on two major components in FY17: the jacketed superconductors needed for toroidal field coil fabrication and its 75% share of the steady-state electrical network for powering the non-pulsed loads on the ITER site. However, at present funding levels, the U.S. is at risk of falling behind on its deliveries, and its hardware contributions could become the pacing items for ITER assembly.


Aerial view of the ITER site in December 2017

**Recommendations for enabling a strong U.S. program in magnetic fusion**

The future of fusion research in the U.S. is captured well by three assessments made by the aforementioned NAS Committee in their interim report:

- "*Construction and operation of a burning plasma experiment is a critical, but not sufficient, next step toward the realization of commercial fusion energy. In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.*"
- "*Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.*"
- "*Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.*"

These three statements convey three important points: 1) U.S. participation in ITER is critical but significantly more R&D remains beyond ITER to realize fusion energy; 2) the U.S. program is suffering due to the lack of new investment; and 3) the U.S. needs a strategic plan that catalyzes research on key enabling areas required in the demonstration of the practicality of fusion energy.

I would like to offer the following recommendations for this Committee in considering the appropriate steps to take to enhance fusion energy development in the U.S.:

[§§] A set of photographs depicting the achievement of key milestones can be found at https://www.iter.org/album/Media/5%20-%20Site%20milestones

- *The U.S. government should establish a clear, coordinated policy on the importance of fusion energy as a national strategic interest.* At present, such clarity is missing and leads to the inability of the U.S. to plan for a program that moves coherently in any specific direction. As an example, the recent charge to the National Academy of Sciences committee read "The committee may assume that economical fusion energy within the next several decades is a U.S. strategic interest." Yet, funding levels in the U.S. are only sufficient to carry out a modest scientific program and well below levels required for even moderately-paced development of fusion energy.[***] In such a climate, discussions on what/how/when to make new investments are extremely challenging as individuals must lean on their own assessments of the appropriate U.S. policy. Given the potential of fusion as a future energy source, it seems appropriate that the U.S. adopt a policy that includes fusion in its national energy plan. This plan should specify certain energy development milestones that serve to both motivate and direct funding in the development of the science and technology of fusion.
- Consistent with developing fusion as a national strategic interest in the next several decades, *the U.S. should make a firm commitment to fully fund the ITER project.* As noted previously, the scope of the ITER project is far beyond anything the U.S. could achieve on its own. For a highly leveraged investment, ITER will provide U.S. researchers with a research platform of unparalleled capabilities and access to burning plasmas. This is a unique and timely opportunity that we should not pass up.
- *The Office of Science, in concert with the U.S. fusion community, should develop a strategic plan that defines a distinctive pathway for U.S. fusion energy development while at the same time taking advantage of the considerable investment that is being made worldwide.* The fusion endeavor is a grand challenge for the nation and the world. As we move closer to achieving fusion, with larger and more fusion-capable experiments, it will become even more essential to engage the best minds from universities, labs, industry in resolving the key challenges. Therefore, such a plan should include investment in new capabilities either through upgrades or new facilities with the goal of delivering world-class research platforms. This will be essential in attracting, engaging, and maintaining top talent that can work together to provide innovative solutions to key challenges, leadership and support for the success of ITER, and the ability to envision, construct, and operate new larger and more complex facilities.

Thank you for this opportunity to share my views on the future of fusion energy research in the U.S. I look forward to working with the Committee members to develop and implement impactful approaches to ensure that magnetic fusion becomes a major part of the U.S.'s energy future.

[***] https://commons.wikimedia.org/wiki/File:U.S._historical_fusion_budget_vs._1976_ERDA_plan.png