WRITTEN TESTIMONY OF WAYNE SOLOMON, PhD

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ENERGY GROUP
GENERAL ATOMICS

BEFORE THE SUBOMMITTEE ON ENERGY
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
UNITED STATES HOUSE OF REPRESENTATIVES

FROM THEORY TO REALITY: THE LIMITLESS POTENTIAL OF FUSION ENERGY

June 13, 2023

Chairman Williams, Ranking Member Bowman, and Members of the Subcommittee:

Thank you for providing me this invaluable opportunity to testify at today's hearing on the promise of fusion energy.

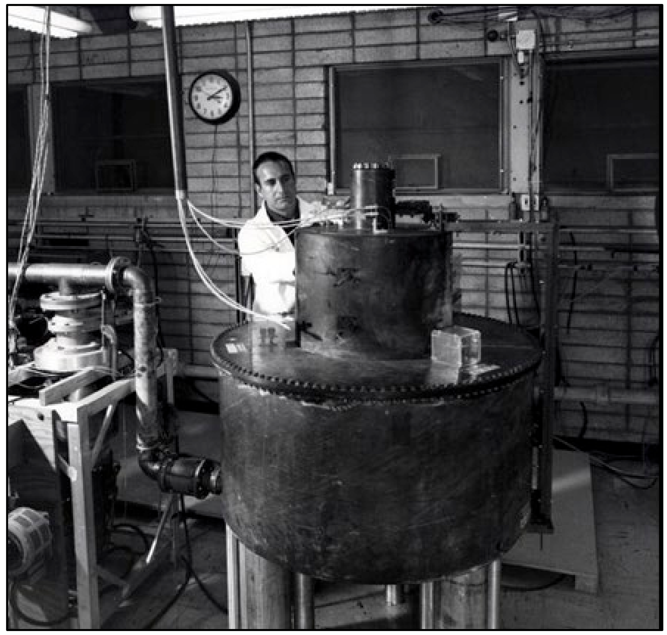
My name is Wayne Solomon, and I am the Vice President for Magnetic Fusion Energy at General Atomics (GA). For over two decades, I have been privileged to collaborate with the world's most exceptional researchers in this field, tirelessly advancing fusion science with the ultimate objective of realizing practical fusion energy. Throughout most of my career, my work has centered on supporting research and overseeing the operations of the DIII-D National Fusion Facility in San Diego, California. Furthermore, I have held leadership roles in two pivotal initiatives within the U.S. fusion community, which established the first comprehensive long-range decadal vision for propelling rapid advancements in fusion.

In the following testimony, I will provide a concise overview of GA's remarkable fusion legacy and its consequential role in the present-day fusion landscape, and recent advancements in the pursuit of commercialized fusion energy.

Overview of General Atomics

GA has a storied history related to fusion. Originating in 1955 as the "General Atomic" Division of General Dynamics, we were at the forefront of researching peaceful applications of atomic energy. Spearheaded by nuclear science luminaries, our pioneering programs included the groundbreaking Doublet I fusion device and the inherently safe TRIGA® research fission reactor. TRIGA is the most widely used research reactor in the world with 66 facilities built in 24 countries on five continents. Over time, our fusion programs expanded, establishing us as the sole U.S. company with significant expertise in both magnetic confinement and inertial confinement fusion. I will delve into these capabilities shortly.

Presently, GA stands as a privately held diversified technologies company, with a global workforce of 12,500 and over 8.3 million square feet of cutting-edge engineering, laboratory, and manufacturing facilities spanning multiple continents. We have evolved into a premier high-tech resource, encompassing the nuclear fuel cycle, electromagnetic systems, remotely operated aircraft, airborne sensors, and advanced electronic, wireless, and laser technologies. Crucially, our core essence remains true to our original mission of advancing nuclear science for the betterment of humanity.


GA's Doublet I device, 1958

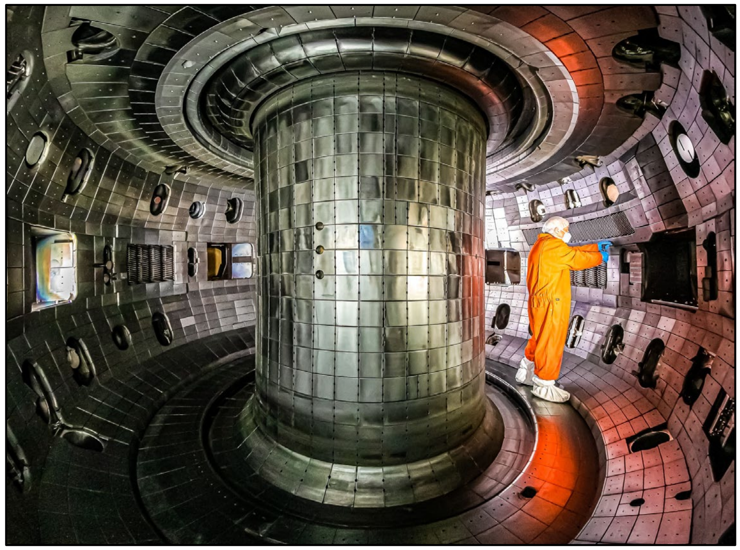
Our Energy Group encapsulates over six decades of fusion expertise and embodies the vanguard of scientific research and innovation in fusion technology. In recent years alone, we have invested upwards of $100 million in internal research and development, propelling breakthroughs in novel materials, state-of-the-art diagnostics, precise control systems, and other pivotal technologies vital for the realization of commercial fusion energy. As fusion start-ups proliferate, our distinguished status as the elder statesman of the fusion community is recognized. Our globally acknowledged capabilities, spanning from comprehensive control systems to our decades of experience operating a large-scale fusion facility with an impeccable track record, position us as one of the foremost private sector fusion enterprises worldwide.

Magnetic Fusion Energy Programs

GA stands at the forefront of the U.S. fusion research program as the leading private sector participant. We proudly consider ourselves steadfast partners in the U.S. government's quest for fusion. In my role as Vice President of Magnetic Fusion Energy programs, I oversee several of these critical collaborations. Today, I wish to emphasize two of these significant activities: GA's work with the DIII-D National Fusion Facility on behalf of the U.S. Department of Energy (DOE) Office of Science, and our active participation in the international ITER experiment.

Throughout my career, I have been closely connected to the DIII-D program. I joined GA in 2016 as Deputy Director of the DIII-D National Fusion Facility after serving as a long-term researcher with the Princeton Plasma Physics Laboratory, stationed at DIII-D. DIII-D, the largest magnetic fusion research facility in the United States, operates as an Office of Science User Facility managed by GA on behalf of the DOE. Renowned for its flexibility, DIII-D boasts an unparalleled array of specialty diagnostic measurement systems, surpassing any comparable facility worldwide.

We take immense pride in the DIII-D program, which is the culmination of GA's extensive fusion research lineage, tracing back to our groundbreaking Doublet I program. DIII-D, a tokamak employing powerful electromagnets to shape and confine plasma, stems from the successes of our Doublet I and Doublet II tokamaks. These accomplishments earned GA the opportunity to construct the Doublet III tokamak, which achieved its first plasma in early 1978. Subsequently, the system was modified to adopt a D-shaped cross-section, known for producing more potent plasmas, thus establishing the DIII-D National Fusion Facility under the DOE's auspices.



The Interior of the DIII-D tokamak, 2022

To attain fusion conditions relevant for energy production, DIII-D's plasma requires heating to temperatures surpassing 100 million degrees Celsius—roughly ten times hotter than the sun's core. At such extreme temperatures, hydrogen isotopes merge (fuse), generating helium and releasing substantial energy.

With a long track record of successful operation, we are on the verge of firing our 200,000th plasma, a testament to our program's efficacy.

DIII-D's achievements with the D-shaped configuration have inspired numerous devices worldwide, including NSTX-U (US), JET (United Kingdom), TCV (Switzerland), ASDEX-U (Germany), JT-60U (Japan), KSTAR (Korea), and EAST (China), as well as the international ITER experiment.

It is crucial to recognize these machines and their research teams as a global fleet collaborating to advance our understanding of fusion. Each device is uniquely designed to offer specific capabilities. DIII-D, representing the pinnacle of flexibility and equipped with world-leading measurement systems, provides unprecedented insight and understanding of tokamak systems. This distinctive versatility, coupled with our scientific rigor, positions DIII-D as the foremost producer of peer-reviewed fusion research.

As a DOE user facility, DIII-D propels the drive towards practical fusion energy. We conduct our research in collaboration with over 650 participants supporting the U.S. program and its research priorities, as well as over 100 institutions worldwide. This publicly funded research is shared through publications, benefiting all.

GA's contract for operating DIII-D undergoes a renewal process every five years, and we have recently submitted our 5-year research plan to the DOE for the upcoming contract period.

Notably, our proposal takes significant strides towards fostering new collaborations with privately funded researchers. As the leading magnetic fusion facility in the U.S., we firmly believe that DIII-D should be accessible to the entire fusion community, accelerating the fastest and most effective pathway to fusion achievement. Already, this approach has yielded fruitful collaborations between the DIII-D program and startup companies, enabling them to leverage our capabilities while maintaining control over proprietary information.

Furthermore, DIII-D assumes a vital role as the United States seeks leadership in the international ITER experiment. The design of the ITER facility draws heavily from DIII-D, featuring a four times larger D-shaped cross-section. This establishes DIII-D as a direct counterpart to ITER, ensuring the optimization of research campaigns.

GA's involvement in ITER extends far beyond DIII-D. We actively collaborate with U.S. ITER, managed by Oak Ridge National Laboratory, to develop various systems for the international collaboration. These include high-power microwave transmission line components that enhance plasma heating capabilities and real-time control software for the ITER plasma. Additionally, we are spearheading the development of specialty diagnostic systems to comprehensively measure different aspects of ITER plasma, further advancing our understanding of plasma physics at extreme temperatures.

Of all our ITER contributions, we are most closely associated with the ITER Central Solenoid—a pulsed, superconducting electromagnet and the most powerful of its kind worldwide. Serving as the "heart" of ITER, it occupies the tokamak's core, driving the plasma's current. To fabricate the Central Solenoid modules for ITER, GA established the state-of-the-art Magnet Technologies Center facility in 2015.

Two modules of the ITER Central Solenoid at GA's Magnet Technologies Center

The scale of the ITER Central Solenoid is difficult to convey in words alone. Upon completion, this 5-story, 1,000-ton magnet will generate 15 million amperes of electrical current within ITER's fusion plasma. For comparison, most LED light bulbs draw less than half an ampere. The magnetic force it produces is theoretically powerful enough to lift an aircraft carrier (weighing approximately 220 million pounds) out of the water and several feet into the air. At its core, it will generate a magnetic field over 280,000 times stronger than the Earth's, while its support structures must endure forces equivalent to twice the thrust of a space shuttle lift-off.

Each coil, standing at 7 feet tall and 14 feet wide, comprises 3.5 miles of superconducting cable. From inception to completion, every module must maintain tolerances of less than 1 mm. Having recently shipped the third completed module to ITER, we anticipate finalizing and delivering the remaining modules by the end of next year. The shipping process is nearly as intricate as the construction itself.

GA was entrusted with this momentous undertaking due to our extensive experience and proven capabilities. It is crucial to emphasize that the Central Solenoid is truly unparalleled, with no backup plan. Its flawless operation is imperative, as without it, ITER operations cannot proceed.

At GA, we also support a dedicated group specializing in plasma theory and computational science. This exceptional team conducts intricate and cutting-edge calculations in plasma physics, harnessing the immense power of the world's largest supercomputers, including the groundbreaking Frontier exa-flop system at Oak Ridge National Laboratory. These simulations act as a digital wind tunnel, faithfully recreating the turbulent motion and energy characteristics of fusion plasma. Significantly, these calculations enable us to forecast and anticipate the enhanced confinement of heat and particles, as well as the fusion performance expected in GA's fusion plant concepts and those proposed by other private fusion entities. This invaluable capability empowers us to refine and optimize the designs, ensuring their efficiency and commercial viability.

Should the committee require additional details on any of these exceptional programs, I would be delighted to provide comprehensive insights.

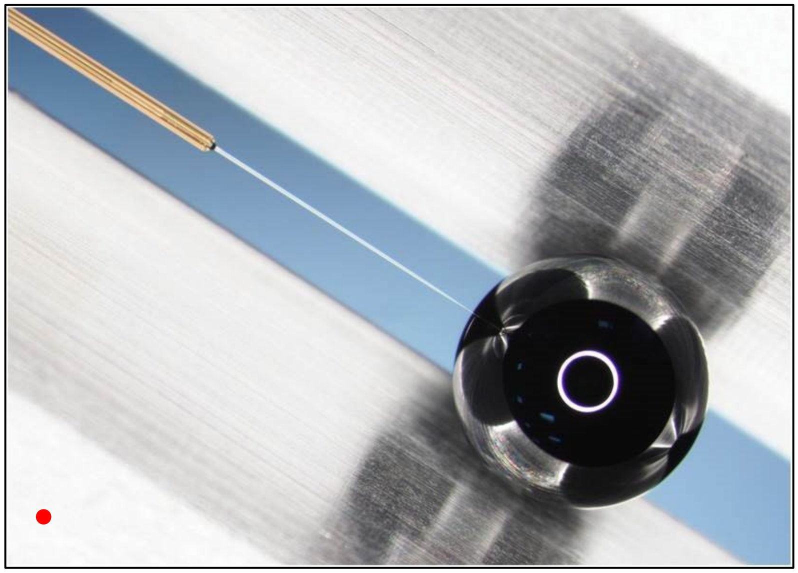
Inertial Confinement Fusion Programs

In addition to GA's magnetic fusion programs, we are also a leader in technologies related to inertial confinement fusion (ICF). ICF recently captured the world's attention when it was announced that the National Ignition Facility at Lawrence Livermore National Laboratory had achieved the first controlled fusion ignition in history.

GA proudly helped to facilitate this achievement by supplying the precision-made components at the very center of the experiment. GA's team processed and prepared the target capsule that was used in the historic experiment, fitted, and proofed the fill tube that added the fusion fuel, fabricated the hohlraum assembly that held the capsule in place, and provided a range of characterization and metrology (measurement) services. These materials were provided to Lawrence Livermore National Laboratory for final assembly ahead of the experiment—part of the long-standing relationship between the two organizations under the ICF program.

The target capsule used in these experiments is approximately the size of a peppercorn, and the fill tube measures just 2 microns wide. For reference, a human hair is approximately 100 microns wide, and a dollar bill is approximately 300 microns thick. GA's talented team of ICF technicians take measurements in three dimensions that are as accurate as 50 nanometers. Again, to put this into perspective, a human fingernail grows approximately 50-60 nanometers per minute.

GA has supported the U.S. ICF research program in close collaboration with the National Nuclear Security Administration since the program's inception. The ICF program plays a critical scientific role in maintaining and enhancing the safety security and effectiveness of the U.S. nuclear deterrent without underground testing by producing thermonuclear burn conditions in the laboratory. ICF uses powerful energy beams, such as lasers, to compress and heat the hydrogen fuel to fusion temperatures and uses the inertia of the fuel itself to confine it long enough for fusion to occur.



A magnified image of the target capsule that achieved ignition at the National Ignition Facility, as photographed by GA technicians after being fitting with the 2-micron fill tube. The red circle (bottom left corner) shows the actual size of the capsule.

As the largest industrial participant in the field of inertial fusion, GA supplies a wide range of critical components, world-leading diagnostics, and associated equipment to the ICF laboratories and other clients.

In addition to being a significant milestone for the NNSA's mission, the achievement of ignition at NIF also has positive implications for commercializing fusion energy, including using ICF techniques, referred to as Inertial Fusion Energy (IFE).

Developing the Fusion Workforce

GA has proudly stood as an ally of the U.S. government and academic programs nationwide, championing the cause of fusion workforce development. Our commitment to nurturing talent within the fusion ecosystem remains steadfast, as we seize the opportunity to shape a new industry that is truly inclusive and representative of the communities it serves. GA stands shoulder to shoulder with other institutions in the fusion community, united in our efforts to dismantle barriers and expand the frontiers of the fusion workforce.

In our pursuit of talent, GA has forged a transformative strategic partnership with the renowned Preuss School, an educational institution under the auspices of the University of California, San Diego. This extraordinary high school stands as a beacon of transformation, boasting a culturally diverse student body of trailblazers determined to be the first in their families to earn a college degree. Through our collaboration, students immersed themselves in GA's laboratories and facilities, gaining invaluable hands-on experience, receiving mentorship, and cultivating the skills necessary to navigate the college application process. Last summer, we celebrated the inaugural cohort, and with great anticipation, we eagerly await the arrival of an even larger class in the coming year.

But our dedication to fostering the fusion workforce extends beyond this exceptional partnership. GA actively engages in the Department of Energy's Science Undergraduate Laboratory Internship (SULI) and Community College Internship (CCI) programs. These initiatives aim to embolden undergraduate and community college students, encouraging them to pursue careers in science, technology, engineering, and mathematics (STEM) by providing immersive research and technical training experiences at the DOE's esteemed national laboratories. By amplifying our collaborations and investing in the fusion workforce, we are committed to breaking down barriers and ensuring that a diverse range of individuals contribute to the advancement of fusion energy.

Looking forward, GA is resolute in its pursuit of new alliances and collaborations that harness our fusion energy expertise. We firmly believe that the future fusion workforce should not be confined solely to those with advanced degrees. We pledge to maintain our leading role in cultivating a vibrant and diverse fusion workforce, one that encompasses individuals from all walks of life, united in their shared vision of realizing the potential of fusion energy. Together, we will forge a path towards a brighter future, where fusion energy becomes a reality for all.

Panelists at a GA-Hosted Congressional Briefing, *Developing a Diverse Fusion Workforce*, co-hosted by the Congressional Fusion Caucus and House Science Committee Chair Frank Lucas (December 2022)

Commercializing Fusion Energy

Allow me to dedicate the remainder of my testimony to the future of fusion, delving into my personal perspectives on what it will take to usher in the first generation of fusion pilot plants (FPPs) and achieve fusion energy on a grand scale.

In October 2022, GA unveiled its visionary concept for a pilot plant, showcasing our commitment to progress in fusion. Our concept centers around a tokamak facility designed to embrace the "advanced" tokamak path, offering the paramount advantage of steady-state operations for uninterrupted power production. We believe this path is the most resilient to transient events that could disrupt plant operations while minimizing cyclic stresses and fatigue. Through our advancements in physics understanding, modeling, and breakthrough technologies that reduce facility size, we aim to expedite the fusion facility construction process and significantly lowered the associated capital costs. Our realistic estimate for completing this facility falls within the mid-2030s.

Armed with extensive experience and a meticulously researched approach, GA submitted its concept to the Department of Energy's Milestone-Based Fusion Development Program. While we were disappointed not to be selected in the initial round, we remain resolute in pursuing our approach, as we believe it to be the most deliberate and plausible path to achieving fusion energy. We look forward to reengaging with the DOE for future opportunities under the program.

Today, there are numerous companies racing towards commercial fusion energy, each employing a variety of approaches. Some of these companies have set ambitious goals to achieve fusion before the decade's end. GA shares in the excitement surrounding this historic interest in fusion and acknowledges the substantial venture capital funding that these companies have attracted. We wholeheartedly support the industry-wide drive to accelerate fusion development and delivery. In parallel with our own efforts, we are actively exploring collaborations with startup companies in the field, seeking opportunities to leverage our capabilities. For instance, we have joined forces with Xcimer Energy in their pursuit of inertial fusion, and we are collaborating with Tokamak Energy on their high-temperature superconducting magnets.

But you asked us to tell you how we view the state of the fusion industry, and while I am optimistic, I am also cautious. There is no single "magic bullet" that can address all the challenges we face in deploying fusion to the grid. There is no singular technology or physics breakthrough that can instantly make fusion economically viable. Critical gaps in fusion technology persist. Successful commercialization of fusion demands a well-coordinated and well-funded effort from both public and private programs. If we genuinely aspire to realize fusion energy, we must allocate resources to advance science and technology on multiple fronts simultaneously. We were delighted to witness the President's Budget Request for a significant increase in the overall fusion budget, which builds upon critical program needs outlined under the *Energy Act of 2020* and the *CHIPS and Science Act of 2022*. Without question, your committee is leading the way.

To deploy fusion commercially in a timely manner, we must possess technical expertise, comprehensive technology, and robust public support. To meet these needs, the federal government must ensure the continuity and expansion of the public program. This serves as the optimal path to position the private sector for success, mitigate risks, and deliver the necessary technologies and capabilities.

Achieving this objective requires the establishment of a new and broad-spectrum public fusion program, as outlined in various reports, including the unanimously adopted 2020 long-range plan "Powering the Future: Fusion and Plasmas" by the Fusion Energy Sciences Advisory Committee (FESAC). This entails substantively increased programs in critical areas where federal funding has been relatively limited in the past, such as the development of materials capable of withstanding the fusion environment and closing the fusion fuel cycle encompassing tritium injection, breeding, processing, and storage. The DOE's request that included the establishment of crucial R&D centers focusing on areas vital to fusion, including the Blanket/Fuel Cycle and Structural/Plasma Facing Materials, as well as Advanced Simulations and Enabling Technologies, is greatly welcomed.

GA has been fortunate to receive multiple federal grants through the DOE's Innovation Network for Fusion Energy (INFUSE) program, advancing critical capabilities related to tritium handling and heat exhaust. Congress should take decisive steps to make additional funding available for technology development related to key systems and processes like the fuel cycle.

Moreover, the public fusion program must experience simultaneous growth in areas that have historically received significant federal emphasis, particularly confinement physics, where ongoing studies in the United States and Europe highlight that confinement quality holds the greatest leverage over the cost of fusion facilities producing electricity. Attention must also be devoted to improving heating and current drive techniques to create and sustain the fusion core, alongside the development of instruments and control techniques applicable to fusion pilot plant environments.

The public program can play a pivotal role in facilitating the commercialization of fusion by continually developing necessary infrastructure and providing accessible pathways for private entities engaged in commercial fusion energy. This demands the modernization and upgrade of existing facilities like DIII-D and NSTX-U to enable cutting-edge research in science and technology and the validation of leading scientific models and simulations in fusion power plant scenarios. Additionally, constructing new facilities and test stands (which enable the testing and demonstration of new technologies) that can tackle various challenges is of utmost importance. As mentioned previously, the leadership team at the DIII-D National Fusion Facility is already taking tangible steps to address these specific requirements.

A successful public program also benefits from the completion of ITER and the establishment of a U.S. ITER research team, leveraging the knowledge gained through our substantial investments. ITER will serve as an invaluable source of information on operating, sustaining, and controlling a burning plasma at the scale of a fusion power plant. This research will hold immense value regardless of the specific fusion concept(s) that ultimately succeed in commercial deployment.

The public program must also provide the private fusion community with access to intellectual, technical, and financial resources, as well as ensuring easy accessibility to public facilities and infrastructure, including advanced computational capabilities required to simulate all aspects of the fusion power system. Furthermore, the government should offer phased funding to businesses, encouraging the development and maturation of their technologies to mitigate risks and expenses associated with vital research and development. This approach will pave the way for the commercialization of laboratory-developed technologies in collaboration with industry partners.

Beyond the technical, the societal impacts of fusion remain largely unknown to the communities that stand to benefit most from its deployment. If we aim for widespread adoption of fusion, we must take deliberate steps to ensure fusion is not only comprehended but also embraced. Local communities and stakeholders must be actively engaged throughout the development and deployment process, shaping decisions that guarantee fusion ultimately enhances their lives. As our industry embarks on sharing our vision for a fusion-powered world, we must exercise caution and refrain from underestimating the immense work that lies ahead.

Conclusion

The President's Fiscal Year 2024 budget request presents a remarkable vision — an unprecedented increase in fusion funding in the history of the U.S. research program. And it now is starting to mirror the levels authorized by Congress. This proposal not only underscores the immense potential of fusion in terms of energy production but also its power to inspire the world. Many of us in this field have dedicated our lives to the pursuit of fusion energy, fully comprehending its profound implications for the planet. We firmly believe that achieving fusion within our lifetimes is an attainable reality.

My deep gratitude goes to the Members of the House Science Committee, the Senate Energy Committee, and the House and Senate Appropriations Committees for consistently prioritizing fusion research and development. Throughout my career, I have developed an appreciation for the challenges that have historically impeded fusion's progress. However, I have also witnessed the astounding strides made by the global community as we unite to overcome these obstacles.

Today, we stand closer to the realization of fusion than ever before. While certain challenges persist, none of them are insurmountable. This is an era brimming with excitement for fusion. With unprecedented interest in commercializing this revolutionary technology, I know that GA will remain a committed partner to both government and industry, spearheading fusion innovations and scaling up transformative solutions. Our unwavering commitment to fusion serves as a strategic foundation, essential for conquering the substantial challenges that still lie ahead on the path to practical fusion power.

Once again, I extend my sincere gratitude for the invitation to testify before you today. I eagerly anticipate addressing any questions you may have.