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Chairman Weber, Ranking Member Veasey, and Members of the Committee, thank you for the opportunity to appear before this committee and to offer testimony on the future of fusion energy research. My name is Mark Herrmann, and I have been the Director of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) since 2014. Prior to becoming NIF Director, I spent 9 years at the Sandia National Laboratories (SNL) holding a number of positions, including Director of the Pulsed Power Sciences Center that is home to the Z Pulsed Power Facility. I have been involved in inertial confinement fusion research for 20 years, beginning my career at LLNL after completing my thesis research at the Princeton Plasma Physics Laboratory.

With my testimony, I hope to convey several points:

- The NIF, along with the Z Pulsed Power Facility, and the Omega Laser Facility at the University of Rochester, are world-leading scientific capabilities funded by the Inertial Confinement Fusion (ICF) Ignition and High Yield Program of the National Nuclear Security Administration (NNSA) as part of the Stockpile Stewardship Program (SSP). All 3 facilities are providing experimental data and workforce training in the high energy density regimes needed to maintain a safe, secure, and effective U.S. nuclear deterrent without further underground nuclear testing.
- One of the major efforts of the national ICF program and the NIF is to achieve fusion ignition in the laboratory to address a grand challenge established at the beginning of the stewardship program. In 2016, NNSA established a 2020 goal for the ICF program to assess the efficacy of NIF for achieving ignition. LLNL and the ICF community developed a 4-year plan to meet that goal, and we are on track at the halfway point. Recently there has been exciting progress in the performance of NIF implosions resulting in a doubling of the fusion yield.
- If ignition can be achieved, it could pave the way to a broad, national, coordinated plan to pursue Inertial Fusion Energy (IFE), which is an innovative, alternative path that is complementary to mainstream magnetic fusion energy research. Currently IFE is not part of the long-term energy R&D portfolio of the U.S. and is not being researched at LLNL.
- The United States is the acknowledged world leader in the area of high energy density science, thanks to investment by the NNSA and DOE, and broad collaborations are exploiting these capabilities to perform world leading science and develop advanced technology. However, the U.S. lead is rapidly shrinking and there are some subfields of HED research where the U.S. is now behind.
- The FY19 President's Budget Request for the ICF program will lead to major reductions in experiments at NIF and the closure of the Omega Laser Facility, substantially impacting our ability to support the Stockpile Stewardship Program, significantly delaying the pursuit of fusion ignition, and disrupting the pipeline of future HED scientists and stockpile stewards.
- The National Academy of Sciences Committee on a Strategic Plan for U.S. Burning Plasma Research has recently released its interim report, which calls for a long term strategic plan for fusion energy.

The National Ignition Facility is delivering for the Stockpile Stewardship Program

Most of the yield of our thermonuclear weapons is generated in the High Energy Density (HED) state. With the cessation of underground nuclear testing in 1992 and the creation of the Science Based Stockpile Stewardship Program (SSP) in the 1990s, it was recognized that an enduring Stewardship Program would require experimental access to HED regimes to ensure the U.S. nuclear stockpile remains safe, secure, and effective without further underground nuclear testing.

The three major U.S. HED facilities funded by the NNSA are NIF, the Z Pulsed Power Facility at SNL, and the Omega Laser Facility at the University of Rochester. These facilities work together in complementary ways to perform the scientific experiments needed for the SSP.

NIF is a football-stadium-sized facility that houses the world's most energetic laser, (approximately 60 times more energetic than any other laser in the world when it was completed in 2009). NIF's 192 lasers can focus into a target smaller than a dime, creating conditions hotter and denser than those found at the center of the Sun. NIF is being used by stockpile stewards at all three weapons laboratories to obtain critical data in support of the SSP. For example, experiments on NIF are:

- Illuminating key weapons physics issues left unanswered when underground testing stopped, enabling sustainment of the current U.S. nuclear stockpile.
- Providing information that is used to develop and certify the approaches to modernizing our U.S. nuclear weapon systems without additional underground explosive nuclear testing.
- Ensuring the nation is aware of and can assess advances in the nuclear weapons of other nations and avoid technological surprise.
- *Providing experimental data that enables tests of our numerical simulation design codes and is used for the physics models critical to the predictive capability that underpins the science-based SSP.*

Over the last four years we have doubled the rate of experiments on NIF, despite flat funding, helping to reduce oversubscription for this unique capability in the world. Recent accomplishments for the Stewardship Program include:

- LLNL scientists have performed experiments to measure the behavior of plutonium at high pressure for the first time --- previously, only theoretical predictions existed. Experimental data agrees with theory in some regimes and differs from theory in others.
- Los Alamos National Laboratory(LANL) scientists have applied NIF to study the hydrodynamic evolution of sheared flows in never before accessed, relevant regimes. These experiments have led to the development of new models to be consistent with the experimental data.
- SNL scientists have used NIF to study the effects of large x-ray and neutron bursts on test objects to help validate codes that are used to ensure our system's nuclear survivability.

In addition to the experimental data that HED facilities like NIF provide, they also play a major role in recruiting and training the scientists and engineers who are the next generation of stockpile stewards. *In the absence of underground nuclear testing, NIF experiments, particularly ignition experiments discussed below provide an important training ground for our current and future workforce in the skills needed to be successful as stockpile stewards.* This experience is so valuable that, in fact, many of the current leaders of the SSP have participated in various aspects of the national ICF program.

NIF is on track to meet the NNSA milestones laid out for fusion ignition research in 2020

At the beginning of the SSP, a grand challenge goal was set of achieving ignition in the laboratory, to address the most challenging outstanding questions in weapons physics. NIF is the only fully operational facility in the world that is capable of achieving thermonuclear fusion ignition in the laboratory via inertial confinement fusion (ICF). Like magnetic confinement fusion research, ICF research focuses on heating a deuterium-tritium plasma up to the extreme temperatures (>50,000,000K) needed for the fusion reactions to self-heat the plasma, potentially leading to the release of more energy than was invested in the creation of the plasma. Unlike magnetic confinement fusion, which uses a large magnetic field in a large volume to confine the plasma, inertial confinement fusion relies on the inertia of the deuterium and tritium fusion fuel squeezed to incredibly extreme conditions (higher density and pressure than the center of our Sun) to provide the confinement.

Thermonuclear fusion ignition is a process that is critical for our nuclear weapons but is tremendously difficult to achieve with the energy levels available in the laboratory. Pursuit of thermonuclear fusion ignition in the laboratory provides the U.S. with insights into one of the least understood aspects of our modern nuclear weapons by providing experimental data to compare with our modern simulations, giving us critical insights into similar processes taking place in our weapons. In addition, the achievement of this grand scientific challenge, would open entirely new vistas of high energy density science and enable access to regimes even more relevant for stockpile stewardship in the future.

In a NIF ICF experiment, the powerful laser beams are directed into the inside of a hollow cylinder of gold (about the size of a pencil eraser) forming a miniature x-ray oven. Inside the cylinder, the x-rays heat a BB sized plastic capsule that contains the thermonuclear deuterium and tritium fuel, causing it to implode on itself at close to one million miles an hour and shrinking in size from a peppercorn to something 1/10 the size of the period at the end of this sentence. This implosion generates the extreme conditions needed for thermonuclear fusion reactions to take place. Our best simulations using our most powerful computers suggest that given sufficient control over the implosion, fusion ignition will take place and lead to the release of significantly more energy than the laser energy NIF used to create the implosion.

Early experiments ending in 2012 fell far short of achieving fusion ignition, despite optimistic projections from our best simulations at that time. A number of additional experiments were then performed to identify the gaps in our simulation capability. In 2015, NNSA chartered a review of the national ignition effort, and based on that review NNSA released a report in 2016, setting up a principal goal of the ignition effort “by 2020, to determine the efficacy of NIF for achieving ignition and the credible physics scaling to multi-megajoules of fusion yields for each of the major ICF approaches”.[*]

The LLNL ignition program, in partnership with LANL, is now half-way through the plan that was developed in response to NNSA’s 2020 goal. As part of that plan - by utilizing clever experiments, advanced diagnostics, and new target designs - we’ve made a number of significant advances in understanding that have translated into improved implosion performance and higher fusion yield.

In fact, in 2017, changes to the targets used in the experiments enabled the fusion yield in the best implosions on NIF to more than double the previous record, to over 50 kJ, or 25x higher than fusion yields in 2012. The best implosions have demonstrated that the fusion plasma is starting to heat itself, a critical step on the path to ignition and akin to trying to light a campfire and having the wood start to smoke. Current supercomputer simulations suggest that a 30% enhancement in the pressure or the

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[*] NNSA report DOE/NA-0044, *2016 Inertial Confinement Fusion Program Framework*

confinement time of this extreme plasma would bring us to the ignition threshold, although it is important to keep in mind that while these simulations are the best we know how to do - they could be wrong.

Furthermore, there are a number of exciting avenues to pursue as we execute the plan to the 2020 goal. New target designs with bigger and better capsules are opening up larger parameter spaces for experiments, new diagnostics are shedding light on the differences between simulations and experiments, and advances in the science and technology of the NIF laser have opened up pathways to a 40% increase in laser energy, which further broadens the space for ignition.

Ultimately the goal of the ignition effort on NIF is two-fold: to achieve ignition (greater than a megajoule of fusion yield) if it is possible, or to determine with high scientific confidence what is preventing ignition on NIF. In the event that ignition is not attainable on NIF, it is critically important that we understand why, as it is essential for the SSP to be aware of this shortfall in our capabilities. It also prepares us for the possibility of using alternate means to achieve ignition, either by modifying NIF or by developing another ignition capable facility.

Progress on Inertial Confinement Fusion could provide an alternative path to fusion energy

If inertial confinement fusion ignition is obtained on NIF, it would be the first time in the laboratory that a fusion reaction released more energy than was used to generate the reaction. Such a breakthrough could form the basis of a possible path to fusion energy that would have significantly different technological and engineering risks 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 IFE research at LLNL.

It is important to acknowledge upfront, like all approaches to fusion energy, that there are a large number of technological, engineering, and scientific 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 yield conditions multiple times per second. There are very significant technical hurdles that would need to be overcome in developing drivers that can operate multiple times per second, in building and injecting ignition quality targets multiple times per second, and in protecting the entire system from the harsh fusion environment associated with large, repeated fusion yields. Furthermore, each of these systems will have to be developed at significantly reduced costs from current levels in order for any energy produced to be economical.

The National Academy of Sciences studied this problem and released an excellent, detailed report in 2013 entitled "An Assessment of the Prospects for Inertial Fusion Energy".[†] A number of conclusions and recommendations were made, including a recommendation to continue progress in target physics research on the various approaches to inertial confinement being pursued on NIF, Z, and Omega facilities. The report was 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".[‡] In my opinion a national, coordinated, broad-based IFE program should await fusion ignition.

Nevertheless the committee also concluded: "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

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

[‡] Ibid.

uncertainties in the future availability of alternatives such as those that arise from unforeseen circumstances."[§]

The idea that a portfolio strategy should include inertial fusion energy R&D is an important conclusion of the NAS report. *This is particularly true because 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.*

As an example of the benefits that would accrue from a small IFE portfolio, a number of promising technologies highlighted in the NAS report as key to eventual IFE systems are making steady progress. In particular, there have been exciting advances in rep-rated laser technology and rep-rated pulsed power technology in the U.S. over the last few years, potentially lowering 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. Research in the magnetic fusion community is advancing the potential of liquid metals as first wall materials for fusion reactors, which could also benefit IFE. Unfortunately, without even a minimal IFE program, the U.S. is not in a position to assess the significance of these advances for a potential future IFE system.

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

As discussed above, the U.S. investments supported by NNSA and the DOE have made the U.S. the world leader in this area of science, giving the U.S. a competitive advantage and demonstrating to the world our commitment to maintaining a safe, secure, and effective deterrent. As an example, when completed in 2009, NIF operated with 60x more energy than the next biggest laser in the world, which was the Omega Laser Facility, also in the US. Now, nearly a decade later, NIF operates with 10-20x the energy of the next most energetic laser, which is in China. A very similar statement could be made about the Z facility 10 years ago, with the second most energetic pulsed power facility located in the U.S. in 2009 and in China today. 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.*

To ensure healthy engagement with the outside community NNSA, has established cooperative research programs on NIF, Omega, and Z that provide a small fraction of the facility experimental time to academic researchers at other institutions. The proposals are judged on their scientific merit and technical feasibility by external scientific committees and the outside researchers are awarded time on NIF, Omega, and Z to leverage these incredible investments for fundamental scientific studies. For example, academic researchers on NNSA facilities have been studying how the fundamental properties of matter change as the materials are squeezed to higher and higher pressures. These questions are of fundamental scientific interest, are important to understand the structure of planets, and could possibly lead to the discovery of new materials with unique properties and potentially commercial applications.

Such science is also of high interest in the world wide academic community and publications from these cooperative research programs frequently appear in Nature, Science, and Physical Review Letters, and other prestigious journals. This research and these publications are an avenue for NNSA researchers to interact with the outside world, and a very effective advertisement for recruiting students to the Laboratories and into the SSP. *Furthermore, the world-class research that our Lab scientists are*

[§] Ibid.

publishing is one of the most visible manifestations of our deterrent, since the credibility of the deterrent ultimately rests on the quality of the people in the stewardship program. Last but not least, several of these academically-led experiments have developed new and innovative approaches to HED science that have then been adopted for use in addressing core SSP questions.

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. direct energy weapons) and our economic competitiveness (e.g. Extreme Ultraviolet Lithography).

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 (note that 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 1990's, LLNL broke the petawatt (10^15 watts) barrier with the construction of the Nova Petawatt. A number of novel and important new 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 on the exciting science in this area were published over the next 20 years. In December, 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:

> "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".[**]

The FY19 President's Budget Request (PBR) for the Inertial Confinement Fusion Program will significantly delay pursuit of fusion ignition as a goal for the SSP, make significant cuts to the National Ignition Facility, and lead to the closure of the Omega Laser Facility.

NNSA's FY19 PBR reduces funding for the national ICF program by more than 20% relative to FY17, a reduction of more than $100M nationally, and reduces funding for the ICF Program at LLNL by $59M-$73M (depending on final FY18 funding level and including effects of cost shift for target fabrication). The budget request also includes drastic cuts to the Laboratory for Laser Energetics at the University of Rochester, an essential partner for LLNL, NIF, and the national ICF program. In particular, the request for LLE is $45M, a reduction of $28M-35M (depending on final FY18 funding level and including cost shift for target fabrication). The budget document states that the Omega Laser Facility will be closed over the next three years. The target fabrication budget for General Atomics and Schafer, which have been

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[**] *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).

strong partners in enabling many of the advances of the national ICF program for decades, has been zeroed. Finally, the academic programs that are key to the field's future are reduced from $9.5M to zero. Coupled with the reductions at the Omega Laser Facility, where many academics and their students perform their research, these cuts cripple our academic partners and could lead to the loss of a generation of graduate students doing research in the field of HED science and discourage students and early career scientists from pursuing careers in this area of HED science.

LLNL is working closely with NNSA and our national partners in the ICF Program to minimize the impact of these cuts should they be enacted and to remain focused on the highest priority deliverables for the SSP. A detailed implementation plan has not yet been developed, but it is our assessment that reductions in funding of this magnitude to the ICF Program will lead to major disruption and reduction in our ability to provide the data needed in support of both near- and long-term SSP deliverables. *We also assess that the cuts will significantly delay the pursuit of fusion ignition and yield on the NIF, and means we will not meet the NNSA goal set out for 2020.* At LLNL, the proposed budget eliminates funding for nearly half of the scientists and engineers working on the ignition effort, representing a significant portion of the U.S. expertise in this area. Since almost every HED experiment supporting SSP has arisen from tools or capabilities initially developed to address the grand scientific challenge of ignition, these cuts will affect the long-term prospects for providing the data needed for the Stewardship program, and negatively affect recruitment and retention of stockpile stewards.

The proposed cuts at LLNL, coupled with the reduction at other sites, will impact every aspect of the operations of NIF. They will lead to a reduction in operating hours and experiments performed (>30%) as resources are shifted to maintain critical skills and fill needed capabilities lost by reductions to partner institutions. The reduction in experiments performed will impact all users of NIF, reducing opportunities for stockpile stewards, greatly reducing ignition research, and reducing opportunities for the academic community and users pursuing other important national security applications on NIF. NIF will also need to significantly reduce its peak laser power and energy, affecting the fidelity of many experiments. Unique experimental capabilities that have been developed for addressing challenging weapons physics issues will need to be placed in cold standby. As such, these proposed reductions will lead a degradation of NIF's capabilities over time. The cuts to the University of Rochester Laboratory for Laser Energetics will eliminate the efficient development of new experimental platforms on Omega that are eventually fielded on NIF, significantly increasing the time it takes to develop platforms needed for weapons physics.

Obviously, if these cuts were to be enacted it would be devastating to our field with impacts beginning today and persisting well into the future. When viewed through the lens of developments around the world, these reductions would slow the U.S. down significantly at a time when the rest of the world is accelerating.

The National Academy of Sciences Committee on a Strategic Plan for U.S. Burning Plasma Research has recently released its interim report.

While the focus of my own research for the last 20 years has been on inertial confinement fusion, I have remained an interested observer in all aspects of fusion energy research. Currently, I am serving on the National Academy of Sciences Committee on a Strategic Plan for U.S. Burning Plasma Research which is focused on magnetic fusion energy research. Our committee, Co-Chaired by Professor Michael Mauel, Columbia University, and Professor Mel Shochet, University of Chicago, has recently released its interim report and is working now on the final report.

A brief summary of the main assessments from our interim report follows[††]:

Any fusion strategy requires a burning plasma experiment.
If the U.S. wishes to maintain leadership in this field, it needs to develop its own long-term strategic plan for fusion energy.

Major Assessment:

- 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 international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources.
- A decision by the United States to withdraw from the ITER project 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.

Why is Burning Plasma Research Important?

Burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components. All efforts to make fusion energy require a burning plasma—an ionized gas like the Sun and stars that is heated by fusion reactions. Although significant fusion power has been created in the laboratory, a burning plasma, which is heated predominately by fusion reactions, has never been created.

In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.

Status of U.S. Burning Plasma Research:

- The U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.
- 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.

If the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy. In the development of the final report, the committee views the following elements as important to its guidance on a long-term strategic plan:

- Continued progress towards the construction and operation of a burning plasma experiment leading to the study of burning plasma,
- Research beyond what is done in a burning plasma experiment to improve and fully enable commercial fusion power,
- Innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and
- A mission for fusion energy research that engages the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

[††] *Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research.* (National Academies Press, Washington, D.C., 2017)

Mark Herrmann

Dr. Mark Herrmann is the director of the National Ignition Facility (NIF), the world's largest laser and a key experimental facility for the National Nuclear Security Administration's science-based Stockpile Stewardship Program (SSP) located at Lawrence Livermore National Laboratory. In this role Mark has leadership and management responsibility for the NIF and the 650 person team that operates, maintains, and develops its new strategic capabilities. Dr. Herrmann works closely with the leaders of the Stewardship program and the national Inertial Confinement Fusion and Experimental Science programs, as well as the National Security Applications and Discovery Science communities, to ensure NIF is delivering for the Stockpile Stewardship Program.

Mark returned to LLNL to become the NIF Director in October 2014 after 9 years at Sandia National Laboratories, where he led research on the use of large magnetic fields generated by the Z facility to create and control high energy density matter. While at Sandia, Dr. Herrmann held a series of staff and management positions, including Director of the Pulsed Power Sciences Center. Prior to joining Sandia in 2005, Mark was a physicist at LLNL, where his research focused on Inertial Confinement Fusion and high energy density science. Dr. Herrmann was awarded a Presidential Early Career Award for Scientists and Engineers, the American Physical Society Award for Outstanding Doctoral Dissertation in Plasma Physics, three NNSA Defense Programs Awards of Excellence, and the Fusion Power Associates Excellence in Fusion Engineering Award. Mark is a fellow of the American Physical Society. He received his undergraduate degrees from Washington University in St. Louis, and his Ph.D. from the Program in Plasma Physics at Princeton University.