Statement of
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Thank you Mr. Chairman, Ranking Member Inglis, and Members of the Committee for the opportunity to appear before you to provide testimony on the Fusion Energy Sciences program in the Department of Energy's (DOE's) Office of Science (SC). I have been Director of the Office of Fusion Energy Science since June 7^{th} of this year. It is a privilege to lead the nation's fusion energy sciences program following a career of scientific research and service at two national laboratories and in research collaborations with national labs and universities. I am thrilled to have joined this Office when the scientific readiness, opportunity, and urgency in fusion are extraordinarily resonant. I am pleased to share with you my perspectives on the status and the strategy for advancing fusion as we enter a new and critical age in its research and development.

Introduction

The pursuit of fusion energy embraces the challenge of bringing the energy-producing power of a star to earth for the benefit of humankind. The promise is enormous -- an energy system whose fuel is obtained from seawater and from plentiful supplies of lithium in the earth, whose resulting radioactivity is modest compared to fission, and which yields zero carbon emissions to the atmosphere. The pursuit is one of the most challenging programs of scientific research and development that has ever been undertaken. A devoted, expert, and innovative scientific and engineering workforce has been responsible for the impressive progress in harnessing fusion energy since the earliest fusion experiments over sixty years ago. As a result we are on the verge of a new age in fusion science during which researchers will undertake fundamental tests of fusion energy's viability. The scientific community's excitement and optimism about our progress and readiness to enter this new era of fusion research is amplified by the high awareness worldwide of the need to fundamentally alter our energy landscape in this century. Fusion can be part of that landscape shift. But it is no secret that fusion on earth is difficult. Establishing a deep scientific understanding of the requirements for harnessing and optimizing this process on earth is critical, and the progress has been dramatic.

The Scientific Challenges of Fusion Energy

The science underpinning much of fusion energy research is plasma physics. Plasmas -- the fourth state of matter -- are hot gases, hot enough that electrons have been knocked free of atomic nuclei, forming an ensemble of ions and electrons that can conduct electrical currents and can respond to electric and magnetic fields. The science of plasmas is elegant, far-reaching, and impactful. Comprising over 99% of the visible universe, plasmas are also pervasive. It is the state of matter of the sun's center, corona, and solar flares. Plasma dynamics are at the heart of the extraordinary formation of galactic jets and accretion of stellar material around black holes. On earth it is the stuff of lightning and flames. Plasma physics describes the processes giving rise to the aurora that gently illuminates the far northern and southern nighttime skies. Practical applications of plasmas are found in various forms of lighting and semiconductor manufacturing, and of course plasma televisions.

At the heart of fusion energy in the stars and on earth is the world's most famous equation, $E = mc^2$, which summarizes our understanding of how mass can be converted into energy. Inside the sun, plasma pressures are high enough that hydrogen nuclei frequently collide and fuse into new atomic nuclei. The end product of these new fused systems actually weighs less than the original nuclei; the "missing" mass is converted into the motion of the byproducts of the collisions, releasing prodigious quantities of energy. The energy released by fusion is largest per unit mass for the lightest elements. Thus, scientists also choose hydrogen isotopes to achieve fusion on earth.

On earth, fusion is in fact routinely created and controlled in our fusion research laboratories -- for example, I've had the privilege of being part of and of leading experiments that have generated millions of watts of fusion power for seconds at a time. In our vision of a working reactor, some of the energy will be captured by the plasma itself, and the plasma will self-heat, enabling more fusion to take place. The energy of the fusion reaction byproducts -- energetic ions and neutrons -- escaping the plasma will be captured and converted into heat. This heat will drive conventional power plant equipment to boil water, generate steam, and turn turbines to put electric power on the grid.

The leading challenge for fusion is stable confinement and control of the hot plasma. When a plasma gets hot enough for fusion to occur, its strong tendency is to expand and cool like any gas. If allowed to do this too quickly, the conditions that enable fusion are lost. If this same hot plasma strikes a material wall before fusion can take place, it also cools and fusion ceases. Thus the hot plasma must be confined for a long enough time away from a material container. The leading approach to fusion energy being pursued in the world is to confine the hot fusion fuel with magnetic fields. The insulating properties of magnetic fields, properly configured, can be extraordinary. In present experimental devices, temperatures of plasmas are found to increase tens of millions of degrees centigrade in a matter of a few centimeters -- from the room-temperature vessel containing the hot plasma into the plasma itself. Another approach is to compress the fuel rapidly so as to reach fusion conditions and rely on the inertia of the fuel itself to keep it combined long enough for fusion to happen. This approach is being studied by the National Nuclear Security Administration (NNSA), and a joint program researching this state of matter is being forged between NNSA and my office.

A second great challenge for fusion is materials that can tolerate the extreme conditions of a fusion reactor. A plasma at a high enough temperature and density to undergo nuclear fusion in a reactor, while generating close to a billion watts of fusion power, will present a uniquely hostile environment to the materials comprising the reactor. The extreme heat fluxes inflicted on a reactor vessel's walls -- at rates of tens of millions of watts per square meter -- present significant materials challenges. Furthermore, in a fusion reactor the materials that will be near the burning plasma will bathe in a harsh shower of neutrons that can displace its constituent atoms and thus alter its strength and other material qualities. Advances in material science will be required to achieve reactor components that can withstand exposure to the enormous heat and neutron fluxes emanating from prolonged fusion burns.

In the last two decades, progress in our understanding of plasma systems and their control requirements has enabled the fusion community to move to the edge of a new era, the age of self-sustaining "burning" plasmas. For both lines of research described above, magnetic and inertial fusion, new experimental plans are being developed to make historic first studies of fusion systems where the energy produced by the fusion process itself is substantially greater than the energy applied externally to heat and control the plasma. In this testimony, I describe the current frontiers for the fusion energy sciences and describe how the research programs of the Office of Science contribute to scientific advances in these areas. I will discuss our program's relationship to international partners and the anticipated benefits of continued U.S. leadership, including benefits to science and to the Nation. I will also describe activities in our own program in the U.S. for building the science that is enabling us to enter the burning plasma era. To begin, however, I would like to briefly describe the origins and scientific breadth of fusion research.

A Brief History of Fusion Energy Sciences Research in the U.S.

The advent of the nuclear age in the mid-20th century led scientists to consider whether the nuclear fusion process could be harnessed on earth for energy production. In the United States, interest in the possibility of controlled fusion dates back even prior to the end of World War II. From 1944 to 1946, frequent and lively discussions of the subject were held among scientists assembled at the Los Alamos Scientific Laboratory, particularly E. Fermi, E. Teller, J. L. Tuck, S. Ulam, J. Wheeler, and R. R. Wilson. In the wake of the Manhattan Project, optimism for fusion energy ran high. Many scientists, flush with excitement and confidence from the rapid success of fission research, expected similarly expeditious progress towards controlled fusion. Most of the basic principles of fusion, if not already known, were formulated at that time, and a number of suggestions were made for achieving controlled thermonuclear fusion conditions. While many of these early suggestions were highly ingenious, all failed to meet the basic requirements of a controlled fusion device. From 1951 until 1958, fusion energy research continued under a classified program named "Project Sherwood." By the mid-1950's, about 200 personnel were involved in the U.S. in magnetic fusion research, designing and testing various approaches for "magnetic bottles" to confine the hot plasma.

By the mid-1950s, it was apparent that the underlying physics of the plasma state was proving to be far more complex and difficult to control than had been anticipated. The research in magnetic fusion was declassified in 1958, and at that time it was seen that the U.S., Soviet, and British-led fusion research programs were neck-and-neck -- and far from achieving a usable energy source. Each program was only capable of producing plasmas that were, according to a standard measure, about ten thousand times lower than required for fusion to generate more heat than was required to create the fusing plasma in the first place. Throughout most of the 1960's, research in fusion progressed through small-scale laboratory experiments and research into fundamental plasma theory. It became clear that cracking the nut of the fusion energy challenge was going to take far more basic physics research than predicted at the program's outset.

Much of the research through the 1960's focused on an approach where the magnetic field for confining the plasma was completely defined by the hardware of the experiment. In 1968, however, a major breakthrough was announced by Soviet researchers. They introduced a clever innovation wherein some of the magnetic field for confining the plasma was created by an electrical current passed through the plasma itself. This led to a dramatic simplification in the magnetic coils needed externally. The announced results were stunning to researchers -- plasma performance measured in terms of confinement quality were said to be improved by an order of magnitude. In fact, the results were so surprising that many in the West did not believe them. In an event extraordinary for the times but emblematic of how science is best carried out, the leader of the Soviet fusion effort opened the door to British scientists in 1969. They brought their own measurement equipment to the Soviet Union and confirmed the Soviet claims -- the plasma quality was far superior to any that had been created in any other experiment to date. The results led to the conversion of U.S. research facilities to this new concept called a tokamak, a name based on a Russian acronym for "toroidal (donut-shaped) chamber with a magnetic coil."

These developments expanded our view of what was possible in fusion research. In the 1970's, progress was rapid, and budgets for fusion research in the U.S. increased as a result of the energy crisis. New research facilities were built across the country, including those at the DOE national labs located at Princeton, New Jersey, Oak Ridge, Tennessee, and Livermore, California. A major industrial research endeavor was also begun through a contract with General Atomics in La Jolla, California. University research grew. The theory and computation efforts that accompanied and supported development and interpretation of these experiments grew as well. International research programs also were ambitious, with the largest facilities in the world being constructed in the United Kingdom and Japan.

Scientific progress was strong through the 1980's, despite declining budgets. Major choices were made in program direction, and the tokamak concept was selected as the leading contender to reach the promised land of creating a sustained, magnetically confined burning plasma on earth. In the 1980's research began on the flagship Tokamak Fusion Test Reactor (TFTR) at Princeton, and mid-decade a remarkable achievement was realized. Temperatures of the plasma fuel reached over 200 million degrees Centigrade -- ten times the core temperature of the sun -- in these magnetically confined plasmas. The flexibility of this experiment proved to be of great scientific value in launching controlled research studies of this plasma state. The exciting TFTR results were joined by rapid progress at the DIII-D tokamak at General Atomics in La Jolla, and a healthy competition grew within the U.S. as well as internationally. At this time, complementary experiments were continued at MIT in compact devices of very high magnetic field. The Joint European Tokamak (JET) in England was the first to use the "high octane" mix of the hydrogen isotopes deuterium and tritium (D-T) that will be used in a first-generation fusion reactor. They soon announced to the world the generation of a few million watts of fusion power, enough to power thousands of homes. The race was on -- TFTR at Princeton began its experimental campaign with the D-T fuel mix, and completed it with experiments in 1994 that generated over 10 million watts of fusion power. The JET experiment ultimately created a record 16 million watts of fusion power in 1997, a result enabled by the larger size of the device as compared to TFTR.

Notably, however, more power was used to heat and control the plasma in each of these cases than was used to create the fusion reactions themselves. The figure of merit used in magnetic fusion, Q, relates the fusion power created to the power used to heat the plasma. The JET experiment yielded a Q of about 0.6. A campfire analogy is that, to date in fusion research, we have been burning wet wood. Remove the external flame, and the fire goes out. Extending the analogy, we have learned a great deal during and since these research campaigns about how to make a fire and how to make a fusion fireplace in which the wood burns itself -- in which we have a self-sustained "burning" plasma.

Today we have to build that fireplace and learn how to best manage the fire in a robust, attractive way. Results from the D-T TFTR and JET studies and those obtained worldwide in other experiments pointed to a common direction, one in which meeting the burning plasma challenge is going to require an increase in scale of the research device. The embodiment of these research conclusions is the design and new construction of the international project called ITER (Latin for "the way"), which is described more fully later in this testimony.

It is important to note for understanding the potential future of fusion research that at least two major research thrusts were developing in parallel to the magnetic confinement experiments that I have just described. First, a seminal paper in 1972 pointed out the potential of the laser, invented in 1960, to be used as the basis of a fundamentally different approach to fusion energy. This approach, called inertial confinement fusion, uses symmetrically-applied exceptionally high-power pulsed laser beams to compress a small pellet of fusion fuel to high enough densities and temperatures for fusion to occur. In this case, the inertia of the fuel itself is relied upon to keep the matter contained long enough for a fusion burn to take place. The National Nuclear Security Administration (NNSA) has been the primary supporter of this line of research, through its aim to develop critical tools for stockpile stewardship. The Office of Fusion Energy Sciences also has a keen interest in inertial fusion, both from the point of view of the richness of the plasma physics -- more on this later -- as well as its potential energy applications.

NNSA's recently completed National Ignition Facility at Lawrence Livermore National Laboratory is the world's leading experimental enterprise in this research, and its work in the emergent field of High Energy Density Laboratory Plasma (HEDLP) physics is supported stateside by related research at other national laboratories, the University of Rochester, and a wide range of university-scale experiments.

Second, the computer revolution had enormous impact on fusion research in both magnetic and inertial fusion. The fusion sciences have been transformed from a largely empirical enterprise to a theory-based dominated by vigorous interaction between those who measure the elusive qualities and behavior of the plasma state in fusion conditions, and those who develop its complex theory and represent that theory in computational models. Over the last twenty years, the scientific basis for our readiness for the next era of fusion energy research has been established through this interaction, anchored in flexible, inventive experiments, continuously growing computational horsepower, and rich physics challenges that have yielded many secrets of the plasma to our probing.

In both magnetic fusion energy science and the linked science of inertial fusion energy, we are at the edge of the burning plasma era. A burning plasma is fundamentally different from plasmas that have been created in research facilities to date; it is only in a burning plasma that the energy confinement, heating, and stability are fully coupled, and the scientific issues associated with creating and sustaining a power-producing plasma can be explored. The importance of moving into this era was strongly affirmed in a 2004 National Academy of Sciences review, "Burning Plasmas – Bringing a Star to Earth." This report recognized that a burning plasma experiment is essential to assessing the scientific and technical feasibility of fusion as an energy source. Its strongest recommendation was that the U.S. fusion science research program confront the rich and important scientific questions that will only be possibly by creating a burning plasma in the laboratory. Even since this report, our scientific basis for entering this new era has deepened.

Allow me to now describe for you the present fusion sciences research program in the U.S., with references to the world-wide effort that supports our entrance into this new age, and the enabling program of this new era -- the ITER project.

The U.S. Research Program Today

In the United States, a broad, multi-institutional program in experiment, theory, and computation is executed through the Office of Fusion Energy Sciences. A national laboratory dedicated to plasma physics and fusion research is located at Princeton, New Jersey, and other national laboratories are funded to undertake research in the fusion sciences as well. Many university partners partake in fusion research at these laboratories and at their own campuses.

A major feature of the program is the research platform provided by three major experiments. These facilities and their predecessors have been crucial for developing the physics basis needed to justify a burning plasma physics program. Today the experimental research programs at the U.S. facilities are scientifically complementary.

These are the DIII-D tokamak at General Atomics, mentioned previously, the National Spherical Torus Experiment (NSTX), at the Princeton Plasma Physics Laboratory, and a compact, high magnetic field tokamak called Alcator C-Mod at the Massachusetts Institute of Technology. Researchers participate in joint experiments conducted between these facilities and are leaders in an international organization that develops joint experiments with facilities overseas as well. U.S. researchers participate in about 75 joint international activities at the present time. These activities have a common aim, namely, to develop the scientific basis for a sound and revealing burning plasma research program and to develop fusion plasma science more generally. The national laboratories are intimately intertwined in the research execution and program leadership at these sites. Significant student populations partake in research there, and their programs are intrinsically collaborative. In part through student participation (about 340 graduate students at this time participate in an aspect of fusion energy science research), these national programs have strong, productive ties with many universities across the nation.

Our portfolio also includes a robust program in innovative plasma confinement concepts, which broadens the fusion program by exploring the science of confinement optimization and plasma stability through a variety of smaller novel devices. The breadth of this program is summarized by the fact that, taken together, these confinement devices allow scientists to study plasmas with densities spanning twelve orders of magnitude.

FES also supports a world-leading theory program, which provides the conceptual scientific underpinning of the magnetic fusion energy sciences program. This program focuses on three thrust areas: burning plasmas, fundamental understanding, and configuration improvement. Theory efforts describe the complex multiphysics, multiscale, non-linear plasma systems at the most fundamental level. These descriptions -- ranging from analytic theory to highly sophisticated computer simulation codes -- are used to interpret results from current experiments, plan new experiments on existing facilities, design future experimental facilities, and assess projections of facility performance. U.S. expertise and capabilities in theory and computation are a lynchpin of the transition to the burning plasma era.

The flagship program of this new era is the ITER project, an international fusion research project being constructed in Cadarache, France, that will realize magnetically confined burning plasmas for the first time. Burning plasma physics as it will be explored on ITER presents at once a grand scientific challenge in its own right and an undertaking of tremendous practical import. The goal of this international research program is to demonstrate the scientific and technological feasibility of sustained fusion power. In the United States, we place high importance on the potential of ITER as a flexible instrument for scientific discovery as well as a demonstration of fusion energy's scientific and technical viability. ITER's overarching goals are the creation of plasmas producing 500 megawatts of power with $Q = 10$ for hundreds of seconds, that is, ten times the fusion power generated by the burning plasma as compared to the power used to heat it, and plasmas of $Q = 5$ for durations of up to an hour. What we learn through ITER will guide our choices in the development of a subsequent demonstration power plant.

Seven members comprise the ITER partnership: China, the European Union, India, Japan, Russia, South Korea, and the United States. Under the formal international agreement that entered into force in 2006, the experiment is to be built in Cadarache, France proximal to a major French nuclear research laboratory. It will be the largest magnetic confinement fusion experiment ever constructed, with a radius of the magnetic donut over six meters, enclosed in structure close to 10 stories tall. The magnets will be superconducting so as to enable long pulses of fusion plasmas. U.S. researchers have played a significant role in identifying the design for ITER. As host, the European Union has responsibility for 5/11ths of the project cost. The remaining six partners, including the U.S., is each responsible for 1/11th share. Contributions of the member states are primarily in-kind hardware components for the project. Annual cash contributions are also made to the ITER Organization (IO) in Cadarache that is responsible for assembling the device and the civil construction of the site. The data obtained from ITER will be shared by all partners.

The U.S. ITER Office (USIPO), located at Oak Ridge National Laboratory, reports to my office and manages the interfaces with the IO and the development of the hardware that are a U.S. responsibility. Most of the funds directed to the USIPO will be spent domestically in U.S. industry to design and fabricate the hardware needed to fulfill our obligations. Examples of what we will deliver include superconducting transformer coils that will reside in the center of the magnetic donut, superconducting strands of wire to be used in the construction of some the other magnets for ITER, and measurement instrumentation systems that will be installed on the device to measure and monitor many aspects of the burning plasma.

The schedule for ITER operations is being developed and refined; the first plasma experiments to commission the device are almost certainly at least 10 years away, with the first burning plasma experiments probably in the mid-2020's. This time scale is an acknowledged frustration of all parties given the urgency of the energy challenge and reflects both the immense technical scope of the project, the fact that the laboratory and its governance are being set up at a green field site, and the added challenges posed by a novel international collaboration. Importantly, the USIPO is vigorously engaged with the IO in Cadarache and other members' domestic agencies in implementing U.S. project management practices in ITER. The Office of Science takes most seriously the imperative that ITER be well managed in both its construction and research phases.

With respect to burning plasma physics and ITER itself, the U.S. research program has been particularly effective in improving the ITER design. For example, the "dynamic range" of the plasmas that ITER will be capable of creating has been significantly increased thanks in significant part to U.S. intellectual leadership. The U.S. fusion program's robust interplay among experimentalists, theorists, and computational researchers in developing complex simulation programs executed on the world's most powerful computers have been and will continue to be essential for preparing for the burning plasma era. This interplay is facilitated by the U.S. Burning Plasma Organization, a community-led endeavor of researchers currently headed by the chief scientist of the USIPO.

As described earlier, there is another form of fusion in the laboratory, inertial confinement fusion, whose science is being pursued and is also on the cusp of the burning plasma era. The National Ignition Facility is slated to explore whether a small pellet of fusion fuel can be ignited in a fusion burn by simultaneously heating and compressing it with the enormous radiant power of its unparalleled laser system. If successful, these experiments will be historic -- analogous to achievement of the first spark ever in an internal combustion engine. Significant scientific and technological development will be required to achieve appreciable energy output per spark and the generation of many sparks per second in an attractive manner.

The branch of plasma physics at the heart of this endeavor, high energy density laboratory plasma physics, studies extreme states of matter known to exist otherwise only in extraordinary systems such as stellar interiors and exploding stars. The National Academy of Science has recognized the importance of this field to energy and the study of astrophysical systems, and has urged the formation of a coherent programmatic home in the Federal R&D portfolio. To this end, the Office of Fusion Energy Sciences is now collaborating with NNSA in launching a research program in this branch of science for the sake of advancing both fusion energy science and the science of these extraordinary systems so as to further understanding of our universe.

Importantly, the U.S. fusion energy sciences program also has ambitions to develop and advance general plasma science in the broadest sense. A number of vigorous university-based programs are deployed across the country. Furthermore, my office supports over 30 joint research efforts with the National Science Foundation to advance general plasma science that extends beyond the immediate needs of the fusion goal. This science can be of high import in describing natural plasma phenomena and also has an impact on the economics of industrial plasma applications. Joint research centers with university-scale experiments are at the heart of these ventures and on shedding light on the phenomena governing plasma dynamics in settings ranging from the industrial to the solar corona.

The Office of Fusion Energy Sciences is currently engaged in a formal strategic planning process aimed at filling scientific gaps in the global research portfolio so as to assert U.S. leadership and maximize U.S. scientific return where it best advances fusion as a whole. For magnetic fusion, a Fusion Energy Sciences Advisory Committee recently identified gaps in scientific knowledge that must be filled so as to maximize ITER's scientific opportunities and to close the gaps between ITER and demonstrating fusion power on the grid. This formal gaps and priorities analysis was followed by a community-based activity that identified the research needs for making such an advance. This Office is developing a strategy by drawing upon this input and assessing strategic opportunities for partnership across the Department of Energy. Based on this input, the scientific challenges for magnetic fusion can be broadly stated as follows:

(1) Understanding and optimizing the burning plasma state. Experiments, theory, and simulation have significantly advanced our understanding of what to expect from a burning plasma, and will continue to do so. The U.S. domestic program will continue to play a strong and world-leading role in preparing for the burning plasma era. But ITER provides the only platform planned to directly test and thus expand and challenge our understanding of this complex physics. Both before and during experiments on ITER, we must strengthen the coupling between experiment, theory, and large-scale computer simulation so as to enable prediction of burning plasma performance beyond ITER's operating range and configuration.

(2) Understanding the requirements for extending the burning plasma state to long times -- days, weeks, and longer. Many aspects of this are pursued in the U.S., and the second ten years of ITER's operation will put our understanding to crucial tests. However, in the next ten years overseas fusion programs are set to assert a stronger role and leadership in part through new billion dollar class research facilities in Europe, Japan, South Korea, and China. We are exploring growing our collaborations to increase their impact and the knowledge returned. And finally,

(3) Advancing the materials science for enduring the harsh fusion plasma environment, for extracting energy, and for generating fusion fuel in situ. We are beginning to outline our plans in these areas and to explore alignments with other energy-related fields in developing a materials and fusion nuclear science program. Common interests in materials research exist across both magnetic and inertial confinement fusion research. Beyond this, we will be exploring synergies in this area between fusion, fission, and defense-related research so as to assess the viability and requirements for a cross-office "Materials for Energy" effort that would make the most out of common needs and diverse resources.

Concluding Remarks

In the next ten years, the U.S. fusion research program will strive to be at the forefront of the burning plasma age, one in which research students grow a strong connection to fusion's future and potential. It will be an age where more is asked of advanced computation than ever, where computer simulations are relied upon to close the gaps between one research step and another, and reduce project costs and increase confidence. It will be an era where single purpose laboratories interact readily with multipurpose laboratories with common incentives and common purpose of advancing energy-related science for all. It will be an era in which the best combination of scientific depth and richness is combined with the highest sense of urgency to help the world address its energy challenges successfully to improve our quality of life.

Thank you, Mr. Chairman, for providing this opportunity to discuss the Fusion Energy Sciences Program at the Department of Energy. This concludes my testimony, and I would be pleased to answer any questions you may have.