The Future of Nuclear Power

Testimony to the U.S. Senate Committee on Appropriations
Subcommittee on Energy and Water Development

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Introduction

Thank you Chairman Alexander, Ranking Member Feinstein, and Members of the subcommittee. I am Dr. Alan Icenhour, Associate Laboratory Director for Nuclear Science and Engineering at the Oak Ridge National Laboratory (ORNL), and I am pleased to participate in this hearing with this distinguished panel today.

Oak Ridge National Laboratory is the largest U.S. Department of Energy (DOE) science and energy laboratory, conducting basic and applied research to deliver transformative solutions to compelling problems in energy and security. ORNL's diverse capabilities span a broad range of scientific and engineering disciplines, enabling the Laboratory to explore fundamental science challenges and to carry out the research needed to accelerate the delivery of solutions to the marketplace. ORNL supports DOE's national missions of:

- Scientific discovery—We assemble teams of experts from diverse backgrounds, equip them with powerful instruments and research facilities, and address compelling national problems;
- Clean Energy—We deliver technology solutions for carbon-free energy sources such as nuclear fission/fusion and solar photovoltaics, as well as energy-efficient buildings, transportation, and manufacturing. We also study biological, environmental, and climate systems in order to advance biofuels, while exploring the impacts of all of these technologies;
- Security—We develop and deploy "first-of-a-kind" science-based security technologies to make the world a safer place.

ORNL supports these missions through leadership in four major areas of science and technology:

- Neutrons—We operate two of the world's leading neutron sources that enable scientists and engineers to gain new insights into materials and biological systems;
- Computing—We accelerate scientific discovery through modeling and simulation on powerful supercomputers, advance data-intensive science, and sustain U.S. leadership in high-performance computing;
- Materials—We integrate basic and applied research to develop advanced materials for energy applications;
- Nuclear—We advance the scientific basis for 21st century nuclear fission and fusion technologies and systems, and we produce isotopes for research, industry, and medicine.

As the Associate Laboratory Director for Nuclear Science and Engineering, I am privileged to lead a talented group of scientists and engineers as we address scientific and technological challenges in both fission and fusion energy, radioisotopes, nuclear modeling and simulation, and nuclear security. Our nuclear fission research and development (R&D) efforts span the nuclear fuel cycle and address the current fleet, as well as future reactors. These efforts include:

- advanced reactor technology development and design;
- light water reactor sustainability;
- research and development of nuclear fuels—increased accident tolerance and understanding the science of used nuclear fuel;
- modeling and simulation, including integrated multiphysics modeling, developing new physics codes, and exploring exascale applications;
- measurement and analysis of nuclear data;
- understanding the science of materials in extreme environments;
- development of new manufacturing and maintenance technologies, and;
- safety analysis and licensing approaches.

The expertise we have established in these areas enables our broader contributions in the areas of nuclear security, safeguards, and nonproliferation-related R&D. As a result, ORNL in partnership with other DOE National Laboratories is well positioned for key contributions toward the R&D needed to meet our nation's energy policy objectives for the next generation.

We recognize that future energy demands will continue to require a mixture of sources that are closely and efficiently tailored to regional resources and needs. The shift to carbon-free energy sources also tells us that nuclear must play a role if we are to meet growing needs, particularly in urban and industrial environments where the baseload demand requires the availability of reliable, large-scale electricity production. As we transition toward a clean-energy economy, nuclear energy must therefore continue to be a meaningful and sustained component of the overall U.S. energy balance.

ORNL Supports Nuclear Power as a Continued Carbon-Free Energy Source

Nuclear energy is the largest clean-air energy source in the U.S. and the only such source that produces large amounts of electricity around the clock. It is a secure source that is not subject to changing weather conditions, unpredictable fuel cost fluctuations, or dependence on foreign suppliers. Nuclear power plants produce no air pollution and do not emit greenhouse gases. These features combine to make nuclear energy an essential part of the overall global energy system. In the U.S. alone, it already provides almost two-thirds of our emission-free generation and about 20% of total electricity, all while producing at a greater than 90% capacity factor.[1]

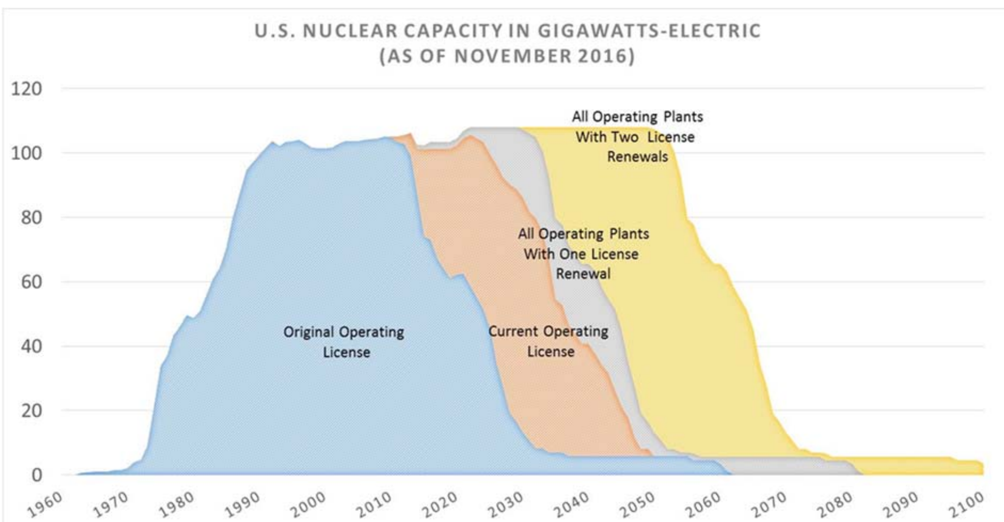
And yet many challenges remain for nuclear energy—both for the existing U.S. fleet, as well as for new reactors. The near-term future of the commercial nuclear power industry hinges upon furthering power uprates, realizing higher fuel burn-up, and operating the existing plants for

[1] Nuclear Energy Institute, 2015 statistics – In the U.S. nuclear energy provides: (a) 62.4% of emission-free generation; (b) 19.5% of electricity, and; (c) produces at a 92.2% capacity factor.

longer lifetimes—all while dealing with market challenges, and also providing confidence in enhanced nuclear safety for both the current fleet and the next generation of nuclear power technology. In the longer term, the next generation of nuclear power technologies offers the opportunity to expand upon past successes by further improving performance, safe operations, and fuel efficiency, while contributing an even greater share of baseload electric power that is carbon-free and environmentally sound.

Avoiding the "Nuclear Cliff"

We are all familiar with the so-called "nuclear cliff," which is the point in time when we will rapidly see retirements of the current fleet of plants as they reach the end of their operating licenses. Recently, one new plant has come on line (Watts Bar Unit 2) and four plants are in the construction phase (Vogtle 3&4 and Summer 2&3). However, six plants have also been closed since 2013[2], with the most recent, Fort Calhoun, shutting down on October 24, 2016. While some remaining plants have been granted marginal capacity upratings, there are also further plants under threat of closure. From a practical perspective, nuclear electric generating capacity replacement is not yet robust and the "nuclear cliff" remains a persistent challenge.



Effect of operating life extensions on current U.S. nuclear generating capacity, depicting original operating license (blue); current operating license (brown), which reflects only the plants that have been granted a license renewal; all operating plants assumed to have one license renewal (grey); and all operating plants assumed to have two license renewals (yellow)

The question is how will we replace that retiring capacity? How can we rapidly innovate and enable affordable and reliable advanced reactor technologies?

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2 The Vermont Yankee Nuclear Power Plant was shut down on December 29, 2014. Another four reactors were permanently closed in 2013 before their licenses expired: San Onofre 2 and 3 in California, Crystal River 3 in Florida, and Kewaunee in Wisconsin. The Fort Calhoun plant shut down on October 24, 2016.

The Next Generation of Nuclear Energy

The United States has historically led nuclear energy innovation, and I believe that we must continue to do so. Nuclear energy has important impacts in terms of our national economy and security. More broadly, nuclear technology capabilities enable many other uses within science, industry, and medicine, such as high energy physics research, deep space missions, imaging, analysis, and isotope-based disease treatment. Our efforts in this area also invigorate our Science, Technology, Engineering, and Math (STEM) capabilities, as we prepare the next generation of scientists and engineers. Our common objective, across the government, academic, and industrial sectors, must be to bring the best of our nation's scientific understanding and engineering prowess to bear on deploying the next generation of nuclear energy technologies. Meeting this objective will enable nuclear power to provide clean, secure, and affordable energy to meet growing demand, and will ensure that U.S. industry is positioned to compete internationally.

While there is a huge potential global impact by deploying advanced nuclear systems rapidly, there are also scientific questions that must be addressed in the process. By using a ***science-based design and licensing approach,*** we can improve upon history, rather than repeat it. The existing fleet of U.S. nuclear plants was developed using empirical engineering approaches. That is to say, systems were initially designed, built, and tested; designs were then marginally improved as operating experience was gained. Billions of dollars were invested in generating operating data to determine what worked best. Because of advancements in scientific capabilities, we have the opportunity to take a new approach. With contemporary science-based tools and techniques, the development phase can be rapidly accelerated in laboratory and high-performance computing environments. Similarly, there are also opportunities to accelerate the licensing phase.

The materials selected for use in nuclear systems directly affect the economics, performance, and safety of power plants. By ***using new materials***, we can improve upon each of these important factors. The current U.S. reactor fleet relied upon alloys available from 1950s and 1960s technology which have incrementally improved. There has been a high bar for introducing new materials into reactors due to regulatory requirements that discourage design change. The opportunity is now at hand to move to a new generation of reactors that will also employ a new generation of advanced materials that can increase safety while reducing cost.

Finally, we have the opportunity to ***see into reactors*** as we could never see before. Obtaining measurements in nuclear environments is particularly difficult due to rapidly changing temperature, fluid dynamics, and radiological environments. However, the information obtained through measurements is critical to our understanding of limits to operating conditions and system lifetime. With modern instrumentation and advanced sensing techniques, a new approach can be taken to optimizing operations and further enhancing safety.

The DOE National Laboratories are the best organizations to assist in rapidly moving nuclear science and engineering toward these new horizons—because the labs rely on the science-based approach, and they field world-class facilities and capabilities. Through research, development, and demonstration of predictive modeling and simulation tools, the labs are largely displacing the old empirical approach. This provides for a new basis for regulatory action and licensing for the next generation of nuclear systems. An important outcome is that ***innovations can be***

introduced more quickly, and advanced designs can be confidently evolved "on the drawing board" without the historic need for a large investment in systems development and testing to gather experimental observations.

Extrapolating atomic-, nano-, and micro-scale processes to engineering-scale properties and performance represents a significant scientific challenge that can be met by the National Laboratories. Not only does engineering qualification of new materials take a long time, but more than 60-year service lifetimes are also difficult to demonstrate. In order to extrapolate what we can do in our laboratories with modern scientific instruments to long-term engineering performance, we must continue to improve our understanding of three key domains:

- Understanding the *mechanisms of material failure* enables improvements to complex alloy chemistry and permits tailoring of new materials to the challenges of operating environments;
- Understanding *long-term material performance* provides the basis for accurate predictive modeling and thus reduces uncertainty in life cycle analysis, and;
- Accurately *characterizing harsh conditions*, such as radiation, high temperatures, and corrosion, further increases the fidelity and thus the reliability of our understanding of engineering performance.

While progress in modeling and simulation is rapidly advancing at the National Laboratories, the need for empirical measurements in extreme nuclear environments will never be entirely overcome. Theory advances most rapidly when validation through testing remains available. Currently, reactor and experimental instrumentation is limited. As a result, reactor operation and safety must all be designed and quantified up front. In the future, the ability to measure detailed environment conditions can be used in real time to inform operations and safety. In-core measurements during irradiation testing and new characterization tools will also improve the development process. Several related issues also need to be addressed, including:

- Survivability of sensors in extreme environments;
- Being able to place sensors in key locations;
- Transmitting data through vessels;
- Reliability of instrumentation system, and;
- Being able to introduce a large number of sensors.

Recognizing the challenges ahead, we must nonetheless move forward deliberately and decisively if we are to avoid the "nuclear cliff," which shows the rapid retirement of a large capacity in a relatively short period of time, i.e., ~100 GWe starting in the early 2030s (depending upon subsequent license extensions for some plants). This 21st century real and present threat creates a palpable sense of urgency that must be translated into action if we are to successfully modernize our nuclear power generating capacity on the needed timescale.

The Road Ahead

Recently, the Secretary of Energy Advisory Board (SEAB) assembled a Task Force that provided expert recommendations for a “Four-Phase Advanced Nuclear Reactor Program.”[3] The phases proceed from technology selection through demonstration plant licensing and culminate in plant operations in preparation for private commercialization. The SEAB report points out that there are many challenges that need to be addressed—some are technology-based, while others are policy-based. The Task Force midpoint estimate is that such a four-phase program would require about 25 years. The future U.S. policy for nuclear energy will be critical. Given the challenges and timeline, decisions are needed with specific goals. It is also clear that rapid innovation will be essential.

The Vital Role of the National Laboratories in Rapid Innovation

If we are to achieve practical realization of ubiquitous carbon-free energy in the next generation of nuclear power, then rapid innovation in nuclear science and engineering is an undeniable prerequisite. While the challenges are great, our national capabilities have also been advanced as a direct result of Federal investments. We have already demonstrated some of the tools needed to accomplish rapid innovation (e.g., modeling and simulation in a high-performance computing environment), but success will require more than just advanced tooling. Rapid innovation also relies heavily on two critical factors:

- Intensive collaboration across the affected sectors–government, academia, and industry, and;
- DOE National Laboratory strategic positioning to assist in systematically identifying and overcoming technical challenges through a science-based approach.

National Laboratories play an important role by providing both the expertise and facilities to work on some of the nation’s most challenging problems. And, with respect to nuclear energy, the National Laboratories are important as we innovate. The laboratories possess unique nuclear technology expertise, ranging from very fundamental science to applications. This expertise must be preserved and further developed for the long term.

The National Laboratories are distinguished by their demonstrated ability to assemble large teams of experts from a variety of scientific and technical disciplines in order to tackle compelling national problems. They also design, build, and operate powerful scientific facilities that are available to the international research community. They work in partnership with universities and industry to train the future science and engineering workforce and transfer the results of their R&D to the marketplace.

[3] Secretary of Energy Advisory Board, Report of the Task Force on the Future of Nuclear Power, September 22, 2016, p. 3.

Intensive collaboration on the next generation of nuclear science and technology will require:

Advancing progress through National Laboratory partnerships -- ORNL works in close partnership with Idaho National Laboratory, Argonne National Laboratory, and other national laboratories to define and solve complex nuclear science and engineering problems—drawing upon the collective national capacity.

Advancing technology through industrial partnerships -- ORNL works closely with industry to move research into the marketplace and collaborates with other private research institutions to expand capabilities, increase the availability of facilities and expertise, and create research and development opportunities for both large institutional labs and small innovative entrepreneurs.

Advancing science through university partnerships—ORNL partners with more than 250 universities and includes several major Southeastern research universities on the UT-Battelle management team. Our core university partners—Duke, Florida State, Georgia Tech, North Carolina State, Vanderbilt, University of Virginia, and Virginia Tech, in addition to the University of Tennessee and Oak Ridge Associated Universities—ensure broad engagement of faculty and students in ORNL's science programs.

Advancing development by leveraging existing assets—ORNL has unique facilities that enable nuclear R&D. Facilities such as our hot cells and glove box facilities allow for the safe handing, experimentation, and analysis of nuclear materials. Such assets are vital to ensure our fundamental understanding of nuclear materials and technologies and to further innovation. Additionally, we use our world-class capabilities such as the Spallation Neutron Source, the High Flux Isotope Reactor, and the Titan high-performance computer to explore materials and phenomena that are important for nuclear applications.

Using the Gateway for Accelerated Innovation in Nuclear (GAIN)—ORNL is working with Idaho National Laboratory and Argonne National Laboratory to implement the DOE's GAIN initiative, which provides the nuclear community easier access to the technical capabilities of the National Laboratories, with the goal of enhancing innovation and moving technologies closer to commercialization. GAIN enables access to nuclear and radiological facilities, testing capabilities, and computational capabilities; as well as information and data.

As reflected by GAIN, in order to deploy new reactor technologies, we must change our approach. The timelines and economics are a hurdle, but they can be overcome through new methods such as increased use of modeling and simulation, use of advanced manufacturing techniques, and development of new materials.

Modeling and simulation has an important role to play—modeling and simulation along with data exploration have joined experiment and theory as the third and fourth pillars of science, allowing researchers who make the most of supercomputers to quickly draw conclusions from complex and copious data. Large-scale computing underpins scientific disciplines including materials science, chemistry, plasma physics, astrophysics, biology, climate research, and nuclear fission/fusion. ORNL supercomputers and support systems for data generation, analysis, visualization, and storage illuminate phenomena that are often impossible to study in a laboratory. Simulations allow virtual testing of prototypes before their actual construction and speed the development of technology solutions.

Advanced manufacturing techniques will add efficiencies—we are also exploring new approaches to the production of qualified components for nuclear energy service, such as additive manufacturing (AM). ORNL is collaborating with equipment manufacturers and end users to advance state-of-the-art technologies and revolutionize the way products are designed and built using AM technology. Drawing on its close ties with industry and world-leading capabilities in materials development, characterization, and processing, ORNL is creating an unmatched environment for breakthroughs in AM.

Advances in materials science are essential—ORNL is a premier materials laboratory where we are researching ways to reduce the time from discovery to use. Additionally, we are exploring how to extrapolate short time experiments and measurements to the much longer times required for components in service. Scientific investigation with neutrons gives researchers unprecedented capabilities for understanding the structure and properties of materials important in biology, chemistry, physics, and engineering. ORNL provides two of the most powerful neutron science facilities in the world—the Spallation Neutron Source and the High Flux Isotope Reactor. Through materials research, scientists are discovering remarkable ways to address our energy needs.

The CASL (Consortium for Advanced Simulation of Light Water Reactors) DOE Energy Innovation Hub Experience

The ORNL experience in conceptualizing, organizing, and executing the CASL mission to provide leading edge modeling and simulation capability to improve the performance of current operating light water reactors represents a valuable model. This is because many of the rapid innovation aspects discussed above were successfully implemented in the CASL methodology. Collaboration via partnerships across the government, academic, and industrial sectors of the nuclear energy community remains a core management principle of CASL, and multiple DOE National Laboratories (ORNL, INL, SNL, LANL) are founding partners with critical roles in addressing specific technical challenges. CASL has been a widely acknowledged success as a direct result of these practices.

CASL has been developing the Virtual Environment for Reactor Applications (VERA) software suite, which was recently recognized with an R&D 100 award. VERA simulates nuclear reactor physical phenomena using coupled multi-physics models including neutron transport, thermal-hydraulics, fuel performance, and coolant chemistry. These CASL tools are now being used in several areas for reactor analysis related to confirmation of vendor analysis tools, analysis of reactor startups, assessment of the risk of Corrosion-Related Unidentified Deposits (CRUD) Induced Power Shift (CIPS), applications to investigate fuel performance, and special studies that provide the physics simulation and fidelity to address issues that industry codes cannot. Test stands have been deployed at Westinghouse Electric Company, the Tennessee Valley Authority, and the Electric Power Research Institute to enable direct industry participation in the test and evaluation stage of CASL technologies.

Examples of CASL applications include:

- Simulation of 14 cycles (20 years) of TVA Watts Bar Unit 1 operation and simulation of Watts Bar Unit 2 startup;
- Westinghouse simulation of the AP1000™ startup and first cycle;
- CRUD and CIPS simulations by Duke Energy, AREVA, and NuScale, and;
- Modeling of accident tolerant fuel designs at Westinghouse.

Setting the Pace for the Future

To further the development of advanced reactor technologies, DOE has established two projects under a Funding Opportunity Announcement (FOA), and ORNL is participating in both projects. In the advanced reactor arena, we are partners on:

- Molten Chloride Fast Reactor: A project led by Southern Company Services, a subsidiary of Southern Company, focuses on molten chloride fast reactors (MCFRs). The effort includes ORNL, TerraPower, the Electric Power Research Institute, and Vanderbilt University. The liquid-fueled MCFR is a molten salt reactor design that offers advantages in terms of its simplicity, fuel cycle, and efficiency. Compared to other advanced reactor concepts, MCFRs could provide enhanced operational performance, safety, security, and economic value.
- Xe-100 Pebble Bed Advanced Reactor: ORNL is also supporting a project led by X-energy to develop the fuel manufacturing methodology needed to supply the Xe-100 Pebble Bed Advanced Reactor. Partners on the project include BWX Technologies Inc., Oregon State University, Teledyne-Brown Engineering, SGL Group, and Idaho National Laboratory. The next-generation design, advanced safety features, and small footprint of the pebble bed high-temperature gas-cooled reactor will enable such a reactor to serve a wide array of community and industry needs while ensuring public safety

Growing National Interest in Advanced Reactors

Collectively, our efforts must consider the entire fuel cycle including the supply chain. Innovation and deployment of reactors does not begin and end with just the reactor. There is clearly growing national interest in the deployment of advanced reactors and the associated fuel cycle as evidenced by the number of summits, symposia, workshops, and other events over the past several years. Last month, at ORNL we hosted our second Molten Salt Reactor Workshop, which was attended by 185 representatives from industry, academia, and government. In February 2016, we hosted the Nuclear Infrastructure Council's Advanced Reactor Technical Summit III, which brought together another 190 technologists focused on topics and methods for improving the cost and deployment time frame of advanced reactors. Once again, industrial, academic, and government organizations were all represented.

Such events reflect the collective sense of urgency in the electric power generating community about the next steps for nuclear energy, and the National Laboratories are an important part of those next steps.

Conclusion

Nuclear energy faces a number of challenges and the National Laboratories play a vital role in helping to meet those challenges. A sustained R&D program is needed, with clear long-term goals. Effective R&D programs will retire technical and regulatory risk, improve economic competitiveness, develop the next generation of scientist and engineers, establish advanced facility capabilities, and address the entire fuel cycle. Rapid innovation will also be essential to achieve success on the time-scale needed to replace capacity and to enable deployment of new technologies.

ORNL is prepared to help address these compelling national challenges, and we have already begun partnering with other National Laboratories, industry, and academia to enable the rapid innovation that will be required. With your continued support, together we can succeed in bringing the best of our nation’s scientific understanding and engineering prowess to bear on deploying the next generation of carbon-free nuclear energy technologies.

Thank you for the opportunity to share my thoughts with the Subcommittee. I request that my written testimony be made a part of the public record, and I would be happy to answer your questions.