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Hearing on the Future of Nuclear Power: Advanced Reactors

Chairman Alexander, Ranking Member Feinstein, and members of the Committee: Thank you for the opportunity to appear before you today. It is an honor to provide this testimony on the future of nuclear energy and the work of Oak Ridge National Laboratory (ORNL) and its partners to accelerate the deployment of advanced nuclear reactor technology.

INTRODUCTION

My name is Thomas Zacharia, and I am director of ORNL, which recently celebrated an important anniversary. On November 4, 1943, the world's first continuously operating nuclear reactor went critical, just 9 months after construction began in the hills of Tennessee.

The X-10 Graphite Reactor quickly achieved its mission of demonstrating plutonium production for the Manhattan Project. When the war ended, it became a key resource for nuclear energy research and development (R&D). In fact, the first nuclear electricity was produced at Oak Ridge in 1948, when heat from the Graphite Reactor was harnessed to drive a toy steam engine, generating enough electricity to light a flashlight bulb.

The construction and operation of the Graphite Reactor drew upon the nation's best intellect and the state of the art in science, technology, and engineering. The national laboratory that evolved around the reactor has been a major contributor to the development and deployment of both naval and commercial nuclear power reactors. Researchers at ORNL continue to work with the nuclear industry to ensure and expand the availability of this important carbon-free energy source.

Today, however, we have tools far beyond the imagination of the Manhattan Project scientists and engineers. The resources available to ORNL, thanks to investments made by the nation, include remarkable capabilities in materials science and engineering, advanced manufacturing, instrumentation and control (I&C) systems, high-performance computing, and artificial intelligence, in combination with unparalleled assets in nuclear science and engineering.

We are confident that focusing these resources and those of our partners on the development and deployment of advanced reactor technologies can have a transformational impact on the challenges facing the nation's nuclear power industry. Our new approach to providing clean, reliable, resilient, and affordable nuclear power for the nation is called the Transformational Challenge Reactor, or TCR.

WHY TCR?

Commercial nuclear power plants provide about 18 percent of the electricity in the United States, and they are by far the largest non-CO_2-producing assets in the national power portfolio. Nuclear power should be an essential element of our low-carbon energy strategy. The U.S. nuclear industry faces challenges, however, in the age of the existing nuclear fleet and the complications of adding new nuclear assets to the mix.

Twelve of the nation's currently operating power reactors, representing a combined capacity of 11.7 gigawatts, are scheduled to retire within the next seven years. A wave of additional retirements is expected in the early 2030s, and the current fleet could essentially be gone by the middle 2050s. Economic pressures could accelerate this decline in nuclear generating capacity.

Since the mid-2000s, the nuclear industry has been looking for ways to modernize nuclear technology and increase its adoption. The principal challenge to the expansion of nuclear power in the United States is the high capital cost of new reactors, which is driven primarily by the costs associated with specialized materials, fabrication of unique components, and construction.

The Tennessee Valley Authority has built several large natural gas combined cycle units in recent years; as a rough rule of thumb, a 1000-megawatt natural gas combined cycle plant can be built for about $1 billion. This provides a price point for any advanced nuclear reactor to be economically competitive.

The nation's only current reactor construction project is the Vogtle expansion project in Georgia. In 2008, the estimated cost of this project to add two new 1,215-megawatt pressurized water reactors to an existing plant was $14.3 billion, and the reactors were scheduled to come on line in 2016 and 2017. Ten years later, the cost has nearly doubled, and completion of the first reactor is still more than two years away.

Small modular reactors (SMRs) are being considered because of their smaller footprints, lower capital risk, less demanding security requirements, efficiency of modular construction in the factory, and other advantages. We do not yet have clear pricing on SMR deployment and operation. The TCR approach has the potential to make SMRs more price competitive with other current energy options, including renewable energy.

The goal of the TCR program is to enable the revitalization of the nation's capabilities in nuclear power by substantially reducing the cost and accelerating the deployment of new reactors. To realize this goal, the program will combine the latest innovations in materials, manufacturing, and machine learning to enable the rapid and economical production of nuclear energy systems that are not limited by the constraints of conventional manufacturing and pre-1970s materials, but that demonstrably meet or exceed the rigorous standards that ensure the safety of nuclear power.

The country's current approach to nuclear energy development and deployment relies largely on materials, manufacturing methods, and designs that were innovative in the 1950s and 1960s, but no longer represent the state of the art. Many of the "advanced" reactors now being proposed are evolutionary concepts that do not take full advantage of recent breakthroughs in science and technology.

The TCR program will address these challenges by developing and demonstrating the disruptive capability needed (1) to create, deploy, and operate innovative nuclear energy systems that exploit 21st century materials and manufacturing processes and (2) to accelerate the certification and qualification of nuclear components and systems for safe and reliable operation by coupling advanced materials and manufacturing with forefront I&C, data analytics, and machine learning.

The program exploits the exceptional skills and resources available at ORNL and other U.S. Department of Energy (DOE) national laboratories, including the specialized facilities needed to support the development, testing, and qualification of nuclear energy systems. It also draws on collaborations with academia and industry-to implement this new approach to nuclear power.

In particular, ORNL is working closely with Argonne National Laboratory (ANL), Idaho National Laboratory (INL), and BWX Technologies, Inc. (BWXT), one of the nation's leading nuclear manufacturers. Our team has prepared an aggressive plan to establish and demonstrate a blueprint for combining advanced manufacturing, data science, and materials science to enable advanced nuclear energy systems. The availability of this fully validated blueprint will dramatically reduce the deployment costs and timelines of nuclear energy components and systems, while maintaining and enhancing safety, simplifying operations, and meeting regulatory requirements.

WHY NOW?

Around the world, other nations are expanding their nuclear power programs to meet rising demands for electricity and reduce their carbon emissions. According to the International Atomic Energy Agency's Power Reactor Information System,[1] China has 46 nuclear power reactors in operation, with another 11 reactors under construction. In India, 22 reactors are in operation and 7 are under construction. Japan restarted five of its existing power reactors in 2018. Nations in the process of adding nuclear power capacity to their energy mix include Bangladesh, Turkey, and the United Arab Emirates. State-owned Chinese and Russian companies are selling nuclear power plants to other countries.

In the United States, the nuclear energy sector is contending not only with the high cost of manufacturing and deploying new reactors and the aging of our current fleet of nuclear power plants, but also with the lack of a clear pathway for disposal of nuclear waste and a complicated regulatory framework that needs updating to support the deployment of advanced nuclear energy technologies. This combination of factors has sharply constrained the development of commercial nuclear energy in the United States. As a result, we are now falling behind the rest of the world in a field that we pioneered.

The decision by Congress to allocate $30 million to the TCR program in fiscal year 2019 enables us to begin shaping a new approach to the challenges of reactor design, manufacturing, licensing, and operation. The TCR program is a key to securing our ability to provide clean, reliable, resilient, and affordable nuclear power for the nation, with benefits to the environment and our national and economic security.

WHY ORNL?

ORNL is DOE's largest science and energy laboratory, with an R&D portfolio that spans the range from fundamental science to demonstration and deployment of breakthrough technologies for clean energy and national security. Our mission explicitly includes both scientific discovery and innovation, so we place a high value on translational R&D—the coordination of our basic research and applied technology programs to accelerate the deployment of solutions to compelling national problems. Our ability to mobilize multidisciplinary teams and to form partnerships with universities, industry, and other national laboratories is a vital asset in this regard.

I have briefly mentioned ORNL's strengths in computing, materials, manufacturing, I&C, and nuclear science and engineering. Our assets include DOE's largest materials R&D program, which supports three scientific user facilities focused on understanding, developing, and exploiting materials (the Spallation Neutron Source, the High Flux Isotope Reactor, and the Center for Nanophase Materials Sciences); the Oak Ridge Leadership Computing Facility

(OLCF), which hosts the world's most powerful supercomputer, Summit, as well as growing capabilities in artificial intelligence and machine learning; the Manufacturing Demonstration Facility sponsored by the Advanced Manufacturing Office in DOE's Office of Energy Efficiency and Renewable Energy; and an extensive program in nuclear energy R&D, supported by specialized facilities and highly skilled staff.

By way of illustrating our ability to deliver on the TCR program goals, here are a few examples of how we have deployed these assets to solve problems in nuclear energy.

Developing new materials for nuclear applications

For the past six decades, the fuel rods in commercial nuclear power plants have been sheathed with corrosion-resistant zirconium alloys. Under normal operating conditions, this cladding material performs well, but a loss of active cooling in the reactor core can have severe consequences, as we saw at Fukushima in 2011. In response to Fukushima, DOE's Office of Nuclear Energy initiated an aggressive R&D program to identify accident-tolerant fuel system technologies. Beginning in fiscal year 2012, ORNL worked with General Electric to develop an iron-based alloy as a replacement cladding material. By mobilizing a team of experts in nuclear engineering, materials science, radiation effects, corrosion, thermomechanics, and alloy fabrication, we were able to produce and test this new alloy, called "IronClad," in six years—much faster than the traditional approach to materials development, which can take twenty years or more. In February 2018, a non-fueled test assembly made with IronClad was placed in Unit 1 at Southern Nuclear's Edwin I. Hatch Nuclear Plant near Baxley, Georgia. This brings us a step closer to deploying a technology that will make our existing reactors even safer than they are today.

Using additive manufacturing to produce reactor components

ORNL's High Flux Isotope Reactor is one of the world's leading research reactors. It is equipped with a set of control elements (an inner cylinder and four curved outer plates) that surround the reactor core. These control elements consist primarily of an aluminum alloy that contains embedded neutron-absorbing materials. They last about 8 years, and fabrication of new ones is both expensive ($3 million per set) and time-intensive (2–3 years).

A team of ORNL researchers undertook the production of these components using ultrasonic additive manufacturing (UAM). They developed an integrated segment production process and verified the properties of the new components using x-ray radiography, optical microscopy, neutron irradiation, and neutronics analysis. The results demonstrate that UAM offers the potential for significant savings in the cost and time required to produce new HFIR control elements.

Developing embedded sensors and controls

Many of the measurement systems used in today's nuclear power plants are based on the same instruments and methods used in the Graphite Reactor in 1943. DOE's Nuclear Energy Enabling Technologies (NEET) initiative supports the development of advanced instrumentation that can operate in the harsh environment of a nuclear reactor. At ORNL and other national laboratories, NEET-sponsored research is leading to new sensors and controls that can be embedded in the components of a nuclear power plant. The TCR program will leverage these efforts to develop and demonstrate how such sensors can be incorporated into reactors, and thereby provide additional operational insights into these harsh environments.

Predicting nuclear reactor performance

Since 2010, ORNL has led a partnership that is working to confidently predict the performance of nuclear reactors through science-based modeling and simulation. The Consortium for Advanced Simulation of Light Water Reactors (CASL) takes advantage of ORNL's leadership-class computers and exceptional strengths in nuclear science and engineering. It also draws on the resources of a formidable set of core partners: three national laboratories (Idaho, Los Alamos, and Sandia), three research universities with strong nuclear engineering programs (the Massachusetts Institute of Technology, North Carolina State University, and the University of Michigan), and three partners from the nuclear power industry (the Electric Power Research Institute, the Tennessee Valley Authority, and Westinghouse).

CASL has connected fundamental research and technology development to develop VERA, a Virtual Environment for Reactor Applications that can simulate the operation of a nuclear power plant. When the Tennessee Valley Authority started up its Watts Bar Unit 2 reactor in 2016, VERA was used to perform hour-by-hour simulations of the new plant's first six months, with predictions providing important data to support the achievement of full-power operations. The results of the simulations agreed closely with the actual operational data—directly demonstrating the predictive capabilities of VERA. In addition, Westinghouse used VERA to simulate the startup of its new AP1000 pressurized water reactor, confirming its engineering calculations.

CASL is also collaborating with the Nuclear Regulatory Commission (NRC) on the use of high-fidelity, advanced modeling and simulation tools in the regulatory environment, with an emphasis in fiscal year 2019 on the use of these tools in a licensing environment for accident-tolerant fuel.

Integrating advanced software and additive manufacturing of reactor components

ORNL and BWXT are already working together to develop a process for nuclear design and manufacturing through the integration of advanced software with additive manufacturing processes. We are leveraging a combination of in situ process monitoring technologies, modeling, and data analytics (1) to rapidly develop the processing conditions for materials used in reactor core and other primary system components and (2) to demonstrate component-level qualification, leading to certification of nuclear materials configured in complex geometries. This project is supported by a $5.4 million cost-share award from DOE's Office of Nuclear Energy.

Developing the workforce needed to support advanced nuclear energy

The design, construction, and operation of nuclear power plants requires a specialized workforce, and the advent of advanced reactor technologies will expand the need for highly skilled workers, who are already in short supply. Several DOE and ORNL programs directly address this need. At ORNL, we are particularly proud of our work with area community colleges and universities to provide students with the industry-recognized credentials and degrees that they need to work in advanced manufacturing. Our Nuclear Engineering Science Laboratory Synthesis program brings nearly 50 students to ORNL each year for internships. In partnership with the University of Tennessee, we offer an interdisciplinary graduate education program in nuclear energy. The Consortium for Advanced Simulation of Light Water Reactors, which we lead for DOE's Office of Nuclear Energy, is supporting the development of a new generation of reactor designers, scientists, and nuclear power professionals. In addition, we are currently assisting two early-career entrepreneurs in the development of an advanced nuclear reactor through our Innovation Crossroads program, which is supported by DOE's Office of Energy Efficiency and Renewable Energy.

WHAT WILL TCR ACCOMPLISH?

During the next five years, the TCR program will design, fabricate, and test the core of a nuclear microreactor, first in a non-nuclear demonstration, and then in a nuclear demonstration. The core will consist of an integrated fuel and cladding structure with embedded cooling channels and sensors for monitoring performance. During the non-nuclear demonstration phase (Phase 1), the core design will evolve as the TCR team works through fabrication, assembly, analysis, and testing of the components of a surrogate core. This illustrates one of the key advantages of additive manufacturing: the ability to design a part that would be impossible to fabricate using conventional techniques, produce it in days or even hours, and then modify the design or the manufacturing process in response to the results of characterization or testing, all at a cost dramatically lower than that of conventional manufacturing.

We are already engaged in designing and fabricating prototype core sections, using resources at ORNL that were previously applied to the development of additively manufactured fuel nozzles for GE aircraft engines. These components can now be manufactured as a single piece, instead of a complex assembly of 20 pieces, resulting in fuel nozzles that weigh 25 percent less, cost

30 percent less, and are 5 times as durable. These fuel nozzles went from a concept 5 years ago to a reality today.

In addition, GE has now demonstrated a fully functional 3D-printed jet engine. More than a third of the components in GE's Advanced Turboprop (ATP) engine, rated at 1,300 shaft horsepower, will be built through additive manufacturing methods. The engine will power Textron Aviation's upcoming 10-person business aircraft, the Cessna Denali. It is going through flight tests this year and will go into full-scale production in 2020. The design went from 855 parts to 12 and the design cycle was reduced from 10 years to 2 years. These innovations are fundamentally changing the aerospace industry.

Additive manufacturing has delivered similar cost savings, efficiency improvements, and energy savings for land-based gas turbines and in the defense industry. The TCR project will demonstrate the same kinds of advances for the nuclear industry.

In parallel with core development and fabrication, the TCR team will develop a "digital twin" of each physical part of the core. These digital twins will have access to all of the data streams captured before, during and after the manufacturing, characterization, and testing of each part, and to the results of sophisticated monitoring of parts in operation. Data analytics will be applied to extract information from these large-volume data streams, and a digital platform that consists of and connects all of these data streams will codify the science behind additively manufactured nuclear components and systems, providing a sound basis for their qualification, certification, and eventual licensing for operation.

The nuclear demonstration phase (Phase 2) builds on the results of the non-nuclear demonstration and includes nuclear core production, employing the advanced manufacturing processes and digital platform developed during Phase 1; nuclear fuel production and delivery; reactor system design, development, and assembly; and the initiation of nuclear testing of a full-temperature critical operating core. The development of the digital platform will be extended in Phase 2 as new materials and technologies are designed, manufactured, and incorporated into the nuclear core. Our expectation is that the TCR program will culminate in the operation of a microreactor within 60 months.

The results of the TCR program will provide a fully validated "blueprint" for combining advanced manufacturing, materials science, and machine learning to enable advanced nuclear energy systems. This blueprint offers a pathway to substantial improvements in nuclear manufacturing and to simplification of the supply chain.

For example, if parts can be rapidly and reliably produced using advanced manufacturing—especially unique parts that are expensive to design and fabricate using conventional techniques—then we can remove the need to maintain an inventory of parts, shorten the duration of plant outages associated with replacement part production (and potential delivery delays), and avoid the stagnation of part designs and the difficulties of introducing new materials for "standard" parts. The direct involvement of industry in the TCR program will facilitate the translation of the program's innovations to practice.

CLOSING REMARKS

The Transformational Challenge Reactor program has an audacious goal and an aggressive schedule. Nevertheless, as we reflect on the 75th anniversary of first criticality at the Graphite Reactor in November 1943, we are inspired by recalling that the first demonstration of a nuclear chain reaction had taken place less than a year earlier, and that the Manhattan Project realized its goal less than two years later.

With the knowledge and tools available to us today, we have both an opportunity and a responsibility to accelerate the development and deployment of clean, reliable, resilient, and affordable nuclear power for the nation. The TCR program can shape a new approach to the design, manufacturing, licensing, and operation of nuclear reactors for which:

- design constraints can be relaxed, and increased complexity can be achieved—because we can build them,
- more efficient regulatory approaches can be used—because of the depth of understanding gained while building them,
- operational envelopes are widened—because we have deep insights into real-time and predictive performance,
- a rapid innovation cycle is achievable—because we can quickly demonstrate concepts,
- flexible and scalable solutions can be deployed—because the technology approaches can be rapidly adapted to new designs, and
- autonomous operation is achievable—because we can adapt approaches already in use to enhance reliability and performance, reduce operator workload, and increase safety margins.

Thank you again for the opportunity to testify. I welcome your questions on this important topic.

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[1] Power Reactor Information System, "The Database on Nuclear Power Reactors," available on line at https://pris.iaea.org/PRIS/home.aspx (accessed 2 January 2019).