Vision and Strategy for the Development and Deployment of Advanced Reactors

2016

Version 21
27 May 2016
Unpublished Draft

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EXECUTIVE SUMMARY

Global efforts to address climate change and meet increasing energy needs require greater use of clean energy sources in the United States and elsewhere. In particular, massive deployment of clean power will be needed by mid-century to meet clean energy commitments negotiated during the 21st Conference of Parties to the United Nations Framework Convention on Climate Change at Paris in December 2015. The safe and secure use of nuclear energy could play an important role in achieving international climate goals while providing economically competitive, continuously available power.

Given the number of nuclear plant retirements expected over the next few decades, however, sustaining a substantial nuclear presence in the U.S. power mix beyond 2050 will almost certainly require the development and deployment of a new generation of advanced reactors. Advanced reactor concepts offer significant potential advantages relative to current light water reactor technology in terms of enhanced safety, lower cost, greater resource utilization, reduced waste management challenges, co-production of process heat for industrial operations, improved proliferation resistance, and easier operation. By exercising a leadership role in advanced reactor technology development, the United States can continue to ensure that national security objectives are embodied in new nuclear generation options for global energy needs. The U.S. Department of Energy (DOE), with stakeholder input, has developed a vision and strategy for supporting the development and ultimate deployment of advanced reactor technology as part of a broader federal commitment to clean energy and national security.

> **Vision: By 2050, advanced reactors will provide a significant and growing component of the nuclear energy mix both domestically and globally, due to their advantages in terms of improved safety, cost, performance, sustainability, and reduced proliferation risks.**

Recognizing that the deployment of new nuclear technologies can take 15–20 years, DOE intends to place significantly increased emphasis on supporting private sector initiatives to advance a new generation of reactor concepts.

> **Goal: By the early 2030s, at least two non-light water advanced reactor concepts would have reached technical maturity, demonstrated safety and economic benefits, and completed licensing reviews by the U.S. Nuclear Regulatory Commission (NRC) sufficient to allow construction to go forward.**

To achieve this vision and goal, DOE's strategy for accelerating the development and deployment of advanced reactors includes six strategic objectives:

1. Enhance the innovation infrastructure for nuclear technologies and vastly improve private sector access to DOE expertise and capabilities through the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative. GAIN provides the nuclear community with access to technical, regulatory, and financial support with the aim of greatly accelerating the progress of new or advanced reactor designs from concept to commercialization. Specifically, GAIN provides a single point of contact for accessing critical experimental resources, computational capabilities and engineering expertise. GAIN was launched in collaboration with the DOE Office of Technology Transition's Clean Energy Investment Center, which will help catalyze private sector investments back into the energy sector.

2. Demonstrate performance and retire technical risks for advanced reactors. DOE will establish new mechanisms to work with private-sector partners to identify priority technology needs and fund research and development (R&D) efforts—both generic and design-specific—that are aimed at reducing technical risk, enhancing safety and security, accelerating development, and improving the economic competiveness of advanced reactors.

3. Support the development of fuel cycle pathways for advanced reactors. Working with industry to develop improved and advanced nuclear fuels is a major objective, both for existing light water reactors and for the entire spectrum of advanced nuclear energy systems. DOE's efforts in this area will focus on ensuring that sustainable low-enriched fuel cycle options are available in the future and on developing the technologies and capabilities needed to enable the safe and secure storage, transportation, and disposal of used nuclear fuel and wastes from existing and future nuclear fuel cycles.

4. Support the establishment of an efficient and reliable regulatory framework for advanced reactors. Industry experts consistently point to the need for an appropriate, efficient and predictable regulatory framework as a high priority for commercializing advanced reactor technologies. DOE and its stakeholders will work with the NRC as the NRC develops new regulatory processes, including efforts to develop design criteria for advanced reactors, staged licensing processes, and preapplication licensability review processes.

5. Maximize the effectiveness of public and private sector investments and explore policy incentives to aid the private sector in accelerating advanced reactor deployment. Specifically, DOE would explore the use of public-private partnerships and technology-specific working groups to identify opportunities for potential government investment that could help advance multiple reactor concepts. In addition, DOE may explore the use of other appropriate incentives to support advanced reactor deployment in collaboration with the Department's Clean Energy Investment Center.

6. Address human capital and workforce development needs. DOE plans to continue funding nuclear-related research projects, scholarships and fellowships through its Nuclear Energy University Program (NEUP) and promote training opportunities through workshops, curriculum development, and joint laboratory, university, and industry projects.

The vision and strategy outlined in this document provide a guide to DOE's expected future programmatic efforts to support the development and deployment of advanced reactor concepts.[1]

[1] This document articulates DOE's vision and strategy for accelerating the deployment of advanced reactors. However, nothing in this document represents or should be construed to represent a binding commitment or decision of DOE, nor should this document be construed as proposing legislation or funding in support of any of the activities, objectives, goals, or initiatives it describes.

Accelerating the Development and Deployment of Advanced Reactors

1. Introduction

Global efforts to address climate change and meet increasing energy needs require greater use of clean energy sources in the United States and elsewhere. In particular, massive deployment of clean power technologies will be needed by mid-century to meet international commitments negotiated at the 21st Conference of Parties (COP 21) to the United Nations Framework Convention on Climate Change at Paris in December 2015. Nuclear energy, which currently accounts for over 60% of carbon-free electricity production in the United States, could play a substantial and beneficial role in achieving greenhouse gas reductions on the scale necessary to meet international climate goals while providing economically competitive, continuously available power.

Even as efforts to expand the contribution from non-greenhouse-gas-emitting energy resources grow more urgent in coming decades, the nuclear energy industry faces substantial challenges. In fact, current projections indicate that U.S. nuclear capacity could begin declining rapidly after 2030 due to a combination of market forces (including strong competition from natural gas generation), remaining useful life considerations, and regulatory effects. Many of the nation's 99 active nuclear units are operating under license extensions that are set to expire in the next 15–30 years. Further license extensions, together with a contribution from a new generation of improved light water reactors (LWRs) and small modular reactors (SMRs) could potentially offset some of this decline, but sustaining a substantial nuclear presence beyond 2050 will almost certainly require the successful development and deployment of a new generation of advanced reactors. These reactors, known as advanced reactors, Generation IV reactors[2] or 21st century reactors, could offer significant advantages compared to state-of-the-art LWR technology in terms of enhanced safety, lower cost, greater resource utilization,[3] reduced waste management challenges, co-production of process heat for industrial operations, improved proliferation resistance, and easier operation.

Because various combinations of these attributes could make Generation IV reactors attractive for markets in the United States and internationally, advanced reactor technologies are already attracting interest, not only from the government sector, but also from the financial and commercial energy sectors. However, unlike LWR technology, which is largely proven, Generation IV reactors still need further demonstration of their performance characteristics and validation of their "value proposition" before broader deployment can occur.

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[2] The evolution of nuclear energy technology is often described in generations. Most commercial reactors that are now in operation are considered Generation II technology. The new LWR plants that have been proposed or are currently under construction, including units at Vogtle and V.C. Summer, are considered Generation III+ technology. For further discussion of the differences between reactor technologies see "Nuclear Reactors: Generation to Generation" published by the American Academy of Arts and Sciences (http://www.amacad.org/pdfs/nuclearreactors.pdf).

[3] Resource utilization in this case refers to the efficient use of available nuclear materials to safely maximize energy output while reducing waste streams.

This document outlines the U.S. Department of Energy's (DOE's) vision and strategy for supporting the development and ultimate deployment of advanced reactor technology as part of a broader federal commitment to preserve nuclear technology as a clean energy option for the future by (1) supporting the safe, economic, and reliable operation of the current fleet of nuclear reactors; (2) pursuing the construction and operation of new large Generation III+ evolutionary light water reactor designs; (3) supporting the development, licensing, and deployment of small modular reactors; and (4) implementing a strategy for the development and deployment of advanced, Generation IV reactor technology. This document and Gateway for Accelerated Innovation in Nuclear **(**GAIN) are intended to be elements of DOE's efforts to communicate with industry, utilities, universities, nuclear organizations and stakeholders on DOE's actions to support development and deployment of advanced reactors as options to meet the country's energy generation needs.

This document is organized as follows: Section 2 reviews the larger policy context for federal investment in a new generation of nuclear reactor technology. Section 3 reviews the goals and objectives of DOE's advanced reactor strategy and describes specific actions DOE is taking or may consider to enhance and improve access to its nuclear innovation capabilities, demonstrate performance and retire technical risk for advanced reactor concepts, develop associated fuel cycle pathways, support the NRC in addressing regulatory challenges, maximize the effectiveness of public/private-sector resources and capabilities, and provide for human capital and workforce needs.

DOE's Vision and strategy for the development and deployment of advanced reactors includes six strategic objectives

2. Policy Context for DOE's Advanced Reactor Technology Strategy

To understand the importance of nuclear energy and the need for continued investment in the development and deployment of improved nuclear technologies, it is useful to examine nuclear energy's place in America's overall energy portfolio, today and into the future. Nuclear energy safely, reliably, and economically contributes almost 20% of U.S. electricity production. The nation's current fleet of 99 commercial reactor units has a combined capacity of 100 gigawatts (GW) and operates at an average capacity factor of 91%. Nuclear power remains the single largest source of carbon-free energy in the United States at present, accounting for more than 60% of non-greenhouse-gas-emitting electric power generation nationwide.

How much nuclear energy might be needed to achieve national climate-change mitigation goals in 2050 and beyond will depend on a number of factors. By way of providing a benchmark, it is useful to consider how much new reactor capacity would be needed to simply maintain nuclear energy's current 20% share of overall U.S. electricity production in light of expected electricity demand growth over the next several decades. Given that overall U.S. demand for electrical energy is expected to grow by about 24% from 2013 to 2040,[4] nuclear generating capacity would need to total at least 125 GW to maintain nuclear energy's current share of electricity production. If meeting the nation's climate and clean energy goals were to require the replacement of a significant fraction of retiring fossil-fuel plants with non-carbon generation options, then another 50 to 100 GW of nuclear energy might be needed in the coming decades. Furthermore, efforts to electrify the transportation sector could lead to significantly higher demand for electricity in general and nuclear energy in particular.[5] Finally, the introduction of nuclear energy for non-electric applications such as desalination or industrial process heat would dictate the need for even more nuclear energy. Therefore, a projection of at least 200 GW of nuclear capacity by mid-century would seem to be a reasonable target for the United States in light of expected demand growth and power sector carbon-reduction goals.

Most of the currently operating Generation II nuclear power plants received license extensions for a total of 60 years of operation per plant. Some fraction of these plants will apply for and receive a subsequent license renewal for an additional 20 years of operation. At the same time, however, market forces, such as low natural gas prices, may cause other units to shut down prematurely. Without further license renewals or an aggressive new build program, overall nuclear capacity in the United States can be expected to decline rapidly beginning in 2030. Further license renewals could potentially delay this decline until 2050, but at some point the current fleet of reactors will have to be retired. A rapid decline in nuclear power in the United States could jeopardize our ability to extend U.S. objectives related to safety, security, and nonproliferation to the international community.

How best to replace the 100 GW of existing U.S. nuclear capacity by mid-century and beyond and how best to fill the potential need for 100 GW of *additional* capacity are important questions for policymakers, technology developers, and power producers ***today*** because the timescales needed to deploy advanced nuclear systems are long – perhaps 20 years.

[4] DOE Energy Information Administration, *Annual Energy Outlook 2015*, page 24.

[5] A 2015 report by the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC), titled *Environmental Assessment of a Full Electric Transportation Portfolio*, examines the potential impact of using electricity to meet a large share of future transportation energy needs—both in terms of greenhouse-gas emissions and in terms of air quality. The report assumes that by 2050 electricity replaces traditional fuels for approximately half of light- and medium-duty transportation and a significant portion of non-road equipment.

Figure 1. Projected U.S. Nuclear Capacity for Different Scenarios

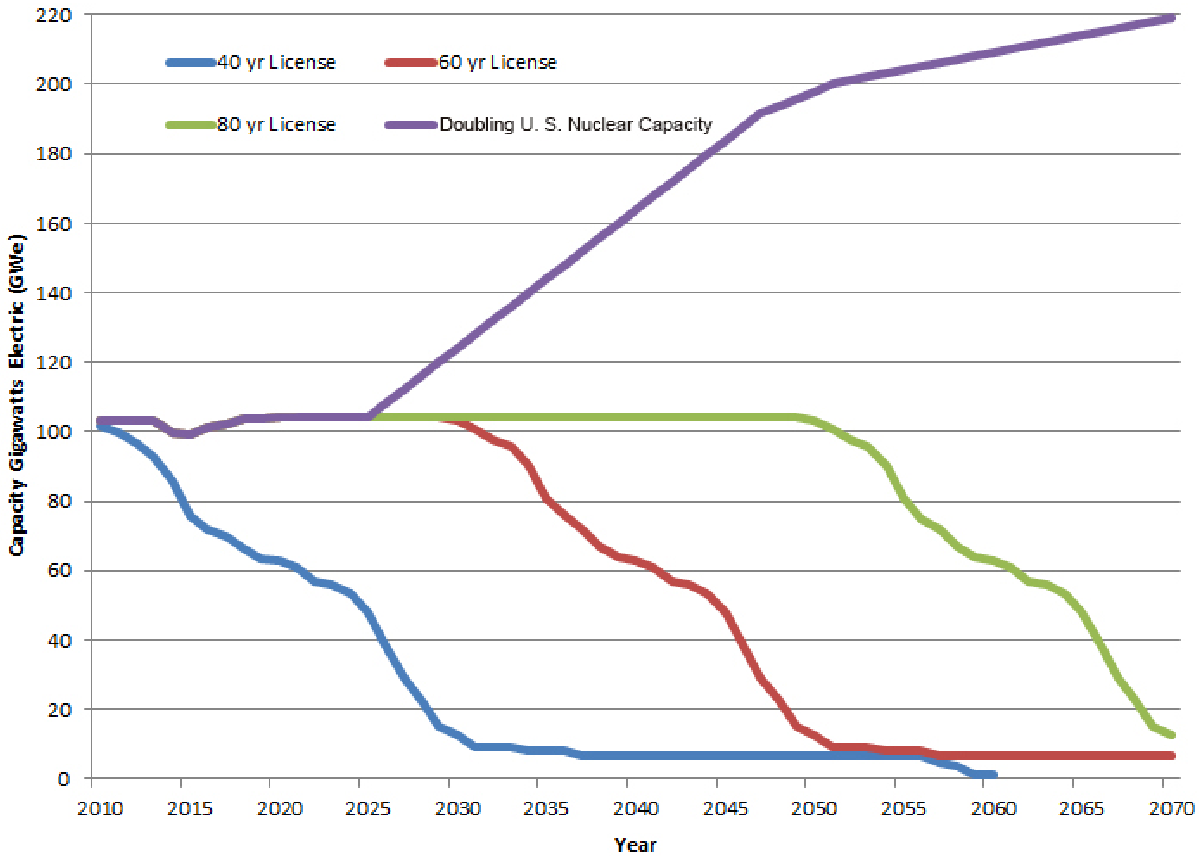


Figure 1 shows the generating capacity available from the current U.S. nuclear power plant fleet under different scenarios for the maximum license period granted to these plants (i.e., 60 years and potentially up to 80 years). The curve labeled "Doubling U.S. Nuclear Capacity" illustrates an approach to climate-change mitigation needs identified at COP 21 (also known as the Paris Climate Agreement). The chart assumes that U.S. nuclear capacity would have to double by 2050 to replace retiring units and provide for certain process heat and transportation needs. The capacity additions needed to achieve the "doubling" curve could come from a combination of new large LWRs, SMRs, and advanced reactors.

There are many good reasons to believe that LWRs will continue to fill a significant fraction of overall demand for nuclear energy in the United States. LWR technology is mature, and the recently completed DOE Nuclear Power 2010 Program led to Design Certification and several Early Site Permits and Construction and Operating Licenses. Currently several new builds of Generation III+ reactors are underway. Uncertainties associated with cost, schedule, and licensing should diminish in a few years. Further, recent progress toward certifying and licensing designs for SMRs, supported by the DOE SMR Licensing Technical Support Program, can be expected to provide power producers with another viable nuclear generating option. Hence, DOE currently expects that several new LWR plants, both large and small, will be built in the coming decades accounting for a significant portion of the needed capacity.

With the retirement of the current fleet over time and other market uncertainties, it is reasonable to expect that the desire to meet greenhouse-gas reduction commitments could drive demand for a substantial contribution from advanced reactors, even accounting for the deployment of a new generation of large LWRs and SMRs. In the context of a 200 GW estimate for new nuclear capacity needed in the 2050 timeframe, a contribution of some 30–50 GW from advanced reactors is not out of the question.

Given the scale of the decarbonization challenge, there is widespread interest in advanced reactor technologies that could offer significant advantages over current LWR technology. At a summit on nuclear energy convened at the White House in November 2015, industry participants expressed interest in developing plans for new, advanced “Generation IV” nuclear plants. This interest in advanced reactor technologies, and that of other stakeholders, including members of the Secretary of Energy Advisory Board, reflects a view that Generation IV systems could deliver more value than LWRs and should be part of the overall power mix. Various combinations of potential attributes – from improved safety and lower cost to advantageous fuel cycle characteristics, easier operation, and proliferation resistance – could make such systems attractive for many markets in the United States and internationally. More importantly, U.S. leadership in these efforts would support international national security objectives with respect to safety, security and nonproliferation of nuclear energy technologies.

For all of these reasons, DOE anticipates that a mix of existing LWRs, new Generation III+ large LWRs, SMRs, and Generation IV advanced reactors could provide for nuclear energy generation into the middle of the twenty-first century. Thereafter, the latter three types of nuclear systems (large Generation III+, SMR, and Generation IV) could be expected to meet a significant portion of America’s clean energy needs.

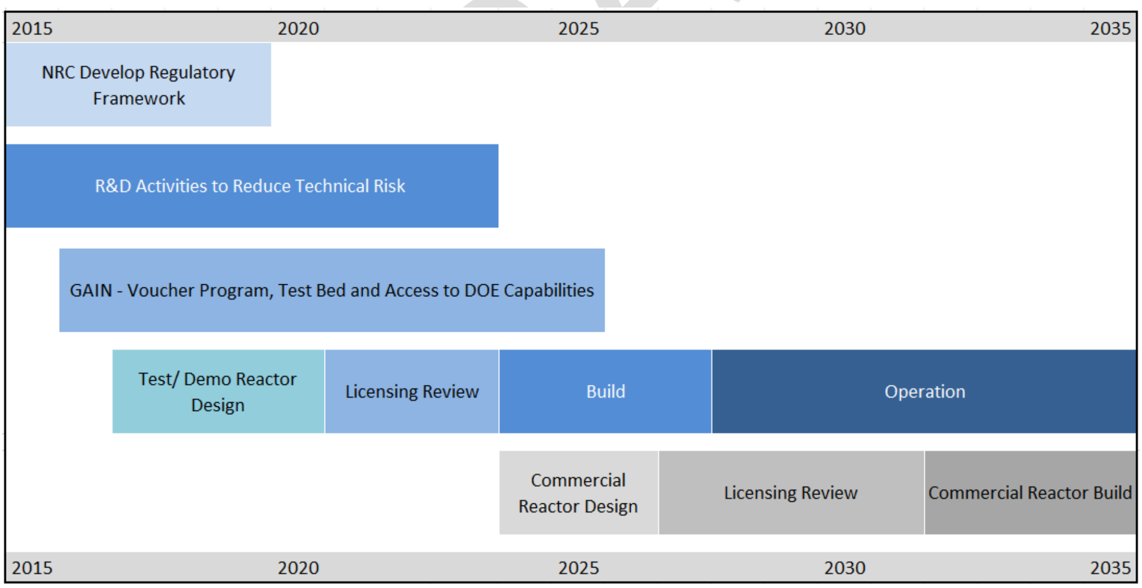
The next section of this document describes DOE’s vision and strategy for advanced reactors. It outlines ambitious development and deployment goals and describes specific actions the Department is taking or considering to achieve these goals.

3. DOE's Advanced Reactor Strategy

As noted in the previous section, growing demand for low-carbon energy coupled with the potential benefits of advanced reactor designs, which operate at higher temperatures and offer inherent safety features, are driving current interest in developing and deploying a new generation of nuclear power systems. Some systems are designed to produce electricity at higher efficiencies and provide process heat for industrial applications such as for the production of hydrogen and synthetic transportation fuels. Liquid metal cooled fast reactors have inherent safety features and could make a substantial contribution to meeting future electricity energy needs while also minimizing the production of long-lived (transuranic) nuclear waste. A further advantage of advanced reactors is that they could be built in large numbers in factory settings. When combined with advanced energy conversion technologies, these reactors could offer a safe and economically attractive source of carbon-free power after 2035. In fact, projections by the U.S. Energy Information Administration indicate that the levelized cost of electricity (LCOE) for advanced nuclear generation in 2040 may be comparable to the LCOE for certain forms of natural gas production.[6] As an additional benefit, development of advanced reactors allows the United States to exercise technology leadership to influence and leverage the deployment of energy options internationally.

Figure 2 depicts a notional schedule for implementing key strategic steps toward advanced reactor deployment.

Figure 2. Notional Timeline for Advanced Reactor Development and Deployment



[6] U.S. Energy Information Administration, *Levelized Cost and Levelized Avoided Cost of New Generation Resources* in the *Annual Energy Outlook 2015*, April 2015 with a release date of Jun 3 2015.

These steps are aimed at achieving DOE's overarching vision for the development of advanced (Generation IV) reactor technology.

> **Vision: By 2050, advanced reactors will provide a significant and growing component of the nuclear energy mix both domestically and globally, due to their advantages in terms of improved safety, cost, performance, sustainability, and reduced proliferation risks.**

Recognizing that the deployment of new nuclear technologies can take 15–20 years, DOE has identified a specific goal for the development and deployment of advanced reactors.

> **Goal: By the early 2030s, at least two non-light water advanced reactor concepts have reached technical maturity, demonstrated safety and economic benefits, and completed licensing reviews by the U.S. Nuclear Regulatory Commission (NRC) sufficient to allow construction to go forward.**

If this goal is met, then utilities can consider advanced reactors as part of their long-range acquisition plans. To that end, DOE has identified several strategic objectives:

1) Enhance the innovation infrastructure for nuclear technologies, and vastly improve access to DOE expertise and capabilities for advanced reactor development through the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative.
2) Demonstrate performance and retire technical risks for advanced reactors.
3) Support industry in the development of fuel cycle pathways for advanced reactors.
4) Support the establishment of an efficient and reliable regulatory framework for advanced reactors.
5) Maximize the effectiveness of private and public sector investments and explore policy incentives to aid the private sector in accelerating advanced reactor deployment.
6) Address human capital and workforce development needs.

While DOE's advanced reactor strategy focuses on U.S. activities, DOE would also continue to engage internationally to leverage mutual capabilities in support of research and development (R&D) and to address specific needs.

3.1 Strategic Objective 1: Enhance the innovation infrastructure for nuclear technologies and vastly improve access to DOE expertise and capabilities through the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative.

Activities to be undertaken in pursuit of this strategic objective encompass three areas: (1) enhancing DOE's innovation infrastructure, specifically including DOE's advanced reactor testing capabilities; (2) implementing GAIN; and (3) improving modeling and simulation tools for advanced reactors. Key benefits of GAIN are to incubate/nurture industry technology development and to assist in commercializing DOE-developed nuclear energy technologies.

DOE's Nuclear Innovation Infrastructure: Currently DOE has two operating thermal spectrum test reactors, the High Flux Isotope Reactor (HFIR) and the Advanced Test Reactor

(ATR). HFIR is used to study advanced materials, perform neutron scattering analyses, and produce isotopes for industry and medicine. The ATR is the only U.S. research reactor capable of providing large-volume, high-flux neutron thermal spectrum irradiation in a prototypic environment for thermal irradiation, thereby enabling researchers to study the effects of neutron and gamma radiation on reactor materials and fuels. Testing at ATR supports research to develop future reactor designs and to test new types of nuclear fuels that reduce waste generation and proliferation risks. Testing at ATR also supports future development programs for the Navy Nuclear Propulsion Program.

While DOE has other facilities such as the Neutron Radiography Reactor and the Advanced Test Reactor Critical Facility, DOE currently lacks the fast neutron test capability that could be used to support the development of innovative advanced reactor concepts and conduct research on advanced nuclear fuel, materials, components, and safety designs. In the past, two facilities provided this capability: the Fast Flux Test Facility (FFTF) and Experimental Breeder Reactor II (EBR II). Both of these reactors were shut down more than 20 years ago.

Advanced Test Reactor at Idaho National Laboratory

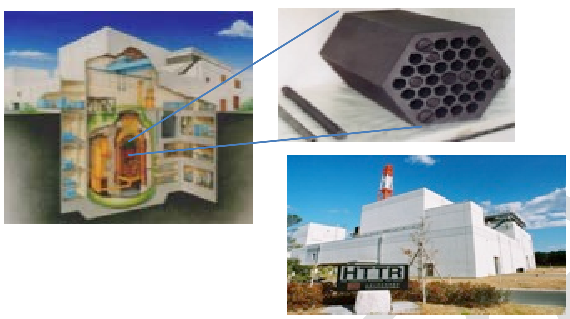
DOE is currently returning the Transient Reactor Test Facility (TREAT) to operation in order to support resumed testing. TREAT was designed to test nuclear reactor fuels under severe reactor-accident conditions and to provide test data using neutron radiography of fuel samples. This capability will be instrumental in proving the safety of advanced reactor designs and facilitating the licensing process.

Transient Reactor Test Facility at
Idaho National Laboratory

DOE also manages a considerable number of post irradiation facilities that can be used to conduct experiments and testing in support of advanced reactor development, including activities that involve the irradiation of nuclear fuels and materials, safety experiments, and post irradiation examination capabilities. These experimental facilities and testing capabilities are essential elements of an R&D test bed for advancing innovative reactor concepts.

In 2015, DOE initiated a planning study to identify test/demonstration reactor options that would be needed to satisfy the materials and fuels irradiation testing and demonstration needs of the national laboratories, industry, and other relevant stakeholders, including NRC licensing requirements. The study examines current capabilities and needs in the context of a national policy to support innovation in nuclear energy. The findings of the study are expected to facilitate DOE planning for follow-on activities.

Finally, because several countries are working to deploy advanced reactor technologies, DOE currently engages in several bilateral and multilateral cooperative efforts with international partners in this area. To meet global climate and clean energy goals, it is considered essential to continue to effectively leverage nuclear capabilities, infrastructure, resources, and technical expertise for the mutual benefit of the international community.



Fuel element for the Japan High Temperature Test Reactor (HTTR). The United States and other countries such as Japan are collaborating to develop advanced reactors.

Gateway for Accelerated Innovation in Nuclear (GAIN): GAIN was established in collaboration with the DOE's Office of Technology Transition's new Clean Energy Investment Center to provide the nuclear community with access to the technical, regulatory, and financial support needed to move new or advanced reactor designs toward commercialization while simultaneously ensuring the continued safe, reliable, and economic operation of the existing nuclear fleet.

Undertaking the R&D activities required to commercialize new or advanced reactor technologies is very expensive and requires special equipment and facilities that are, in many cases, unique to DOE. By helping researchers and developers match their needs to DOE facilities and expertise, GAIN will greatly accelerate the normal development cycle for translating ideas to products.

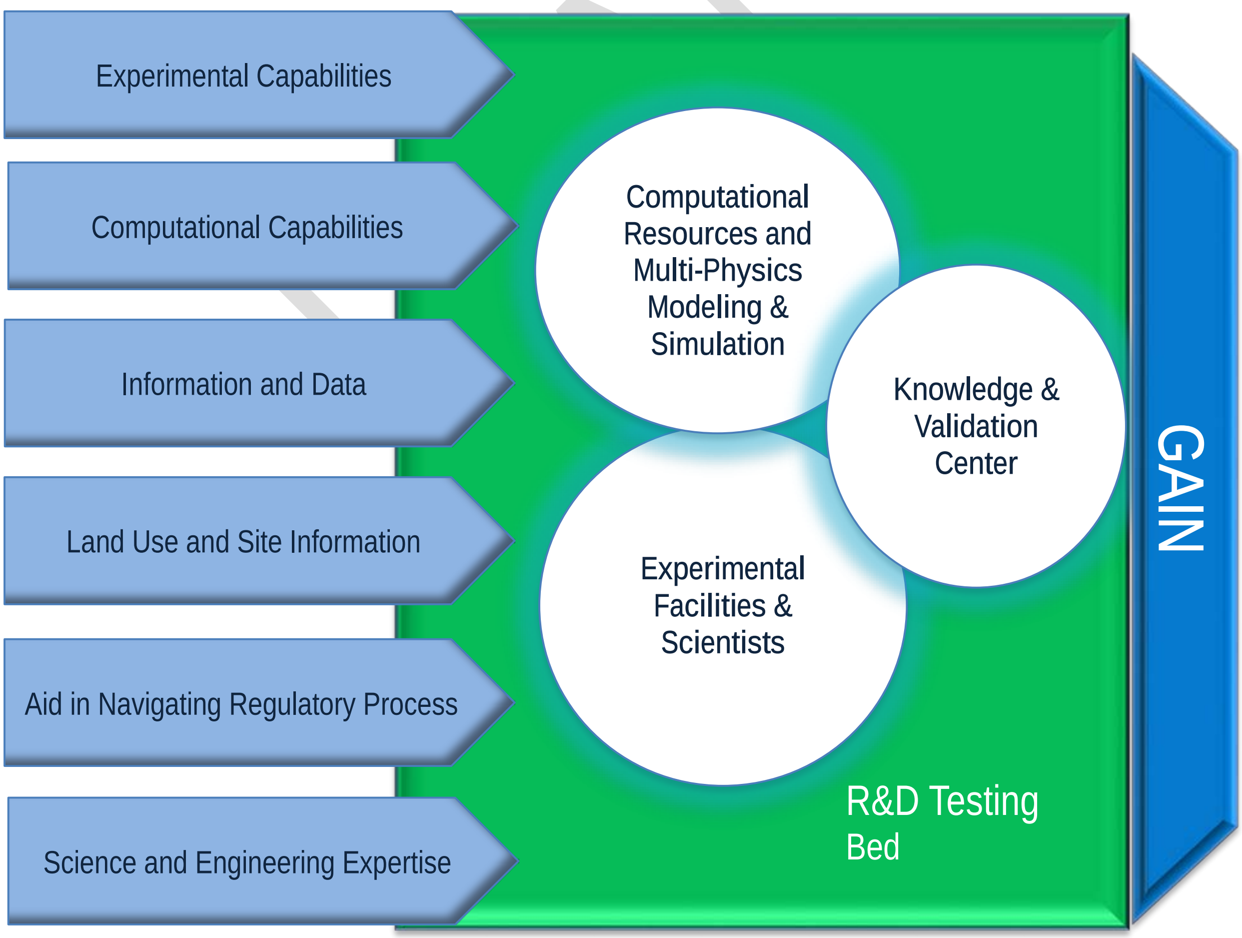
Several different kinds of resources and capabilities are accessible through GAIN:

- Experimental capabilities. The primary emphasis is on nuclear and radiological facilities but GAIN also provides access to other testing capabilities (e.g. thermal-fluid test loops, control systems testing, etc.).

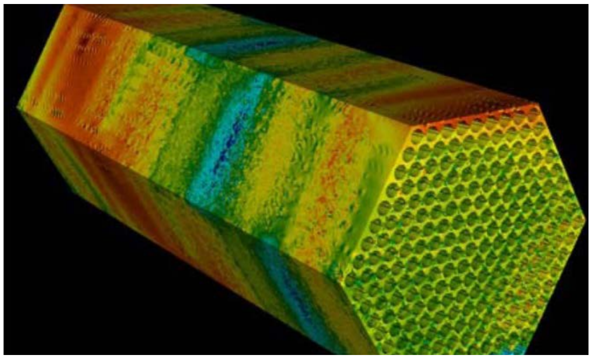
- Computational capabilities along with state-of-the art modeling and simulation tools.
- Information and data through the Knowledge and Validation Center.
- Land use and site information for demonstration facilities.
- Assistance with navigating the regulatory process.
- Science and engineering expertise and experience.

GAIN, through the Nuclear Science User Facilities (NSUF) program, provides a single point of contact for university and industry researchers interested in a wide range of nuclear energy related capabilities and expertise. GAIN also includes a voucher system designed to provide the nuclear community with access to technical, regulatory, and financial support for moving new or advanced reactor designs toward commercialization. The voucher system is expected to support small business participation through cost-shared projects at various facilities. Access to information and data would be provided through the Knowledge and Validation Center. Initially, Idaho National Laboratory (INL) is serving as the GAIN integrator, coordinating access to nuclear energy-related capabilities across the DOE complex (Figure 3). DOE will also seek to leverage GAIN internationally.

Figure 3. Gateway for Accelerated Innovation in Nuclear (GAIN) Framework



Advanced Modeling and Simulation:
Designing advanced reactors and verifying their safety characteristics requires improved tools for modeling and simulating diverse phenomena including neutronics, thermal fluid dynamics, and structural mechanics. Improved modeling and simulation capabilities increase the fidelity and accuracy of reactor design and safety calculations. To develop these capabilities, DOE plans to exploit modern computational hardware and enabling tools for scientific computing, including tools for meshing complex geometries and visualization tools that can aid researchers' understanding of calculated reactor behavior.



Simulation of coolant flow relative temperatures around a sodium-cooled fast reactor fuel bundle performed under DOE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program

These improved capabilities would make reactor simulation more predictive (reducing the need to rely on calibration and conservative margins to compensate for potential inaccuracies) and improve researchers' ability to characterize prediction uncertainty. Improved accuracy and better integration of capabilities also facilitates design optimization to achieve the best balance between cost and performance. Development of appropriate methods, data, and codes also supports regulatory review of advanced reactors to ensure their safety.

Enhancing Nuclear Innovation Infrastructure and Vastly Improving Access

To enhance the nation's nuclear innovation infrastructure, DOE plans to improve its experimental, testing, and simulation capabilities. DOE also plans to vastly improve access to DOE expertise and capabilities. Key activities include implementing the Gateway for Accelerated Innovation in Nuclear (GAIN) and completing the planned return of the Transient Reactor Test Facility (TREAT) to operation to support the resumption of testing. DOE will consider the results of an advanced test/demonstration reactor planning study to identify new test and/or demonstration reactor needs to support the development of advanced reactor technologies. As part of its advanced reactor strategy, DOE will also pursue the further development of nuclear and non-nuclear experimental test bed capabilities and modeling and simulation capabilities. GAIN aims to provide greater access to experimental, testing, and modeling and simulation capabilities; facilitate use of the DOE nuclear technology database; and promote broader engagement with industry to understand technical needs. GAIN includes a voucher system and access to information and data to support moving reactor designs toward commercialization. Finally, DOE will explore options for adding an element of international collaboration to GAIN and the Nuclear Science User Facilities (NSUF) program.

3.2 Strategic Objective 2: Demonstrate performance and retire technical risks for advanced reactors

The nuclear energy industry is both the technology provider and customer for advanced reactor technologies. For the last few years, DOE has been interacting with private-sector partners to align its R&D investment decisions with the industry's most pressing needs. These interactions have helped DOE identify, through a technical review panel process, technology needs that (1) are being addressed by additional R&D investment and (2) would accelerate the retirement of technical risk. Several industry-led R&D efforts were funded through this process. In addition DOE has embarked on efforts to fund two advanced reactor concepts to accelerate their maturation.

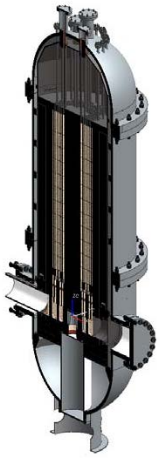
DOE also performs targeted research at its national laboratories (generic and design-specific, as informed by industry needs) to solve technical issues that reduce technical risk, enhance safety and security, accelerate development, and improve the economic competiveness of advanced reactors. This research to address technical risk reduces technical uncertainty concerning innovative aspects of new designs and assists multiple companies. Current research is focused on high-temperature reactors (HTRs), liquid metal cooled fast reactors (LMFRs), and salt cooled reactors. HTR research is focused on developing innovative fuel forms and advanced high-temperature materials. Gas Fast Reactor (GFR) research is centered on silicon carbide materials research. LMFR research is focused on concept development and establishing component-testing capability. Research on salt cooled reactor concepts includes university-led work on fluoride high temperature (FHR) reactors and laboratory-based plans to examine molten salt reactor (MSR) technology. DOE also conducts crosscutting R&D on advanced reactor modeling and simulation, code development and validation, and development of advanced manufacturing capabilities based on identified needs. Other DOE work examines approaches for using nuclear energy as part of an increasingly diverse electricity generation mix. In addition, through engagement with other offices such as Advanced Research Projects Agency – Energy (ARPA-E), DOE can assist industry in such areas as use of new battery technologies.

In sum, DOE's strategy for reducing technical risk and improving the economics of advanced reactor concepts includes continued R&D, support for industry cost-shared R&D, and assessment of future test and/or demonstration reactor needs to inform the Department's future investment decisions.

Mechanisms Engineering (Sodium) Test Loop at ANL

DOE's other near-term efforts to engage industry partners include work with the Electric Power Research Institute (EPRI) to identify utilities' research, development, demonstration and deployment needs related to advancing the commercialization of advanced reactors. DOE also participates in activities to strategically support advanced reactors with the American Society of Mechanical Engineers, the American Nuclear Society, the U.S. Nuclear Infrastructure Council, and the Nuclear Energy Institute's Advanced Reactor Working Group, which includes reactor vendors, suppliers, and utilities interested in supporting the development of advanced reactors.

In addition to engaging internationally to leverage infrastructure capabilities, DOE will continue to pursue bilateral and multilateral collaborations aimed at retiring technical risks associated with the deployment of advanced reactors.



High Temperature Test Facility
at Oregon State University
(Scaled Electrically Heated High
Temperature Gas Reactor Test Facility)

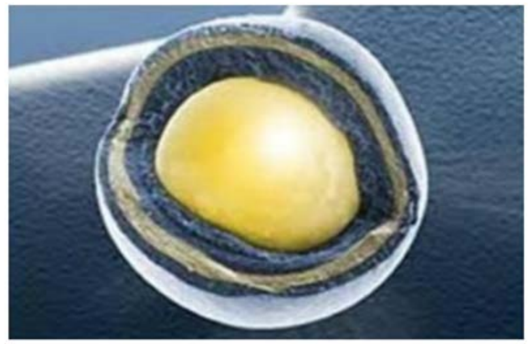
Brayton Cycle Test Loop
Sandia National Laboratories

Retiring Advanced Reactor Technical Risk

DOE will pursue a multifaceted set of efforts to retire technical risks associated with advanced reactors. Specifically, DOE plans to solicit industry input on R&D needs, prioritize plans, and conduct R&D in support of advanced reactor development. These efforts would include traditional laboratory R&D and relevant research projects selected through the Department's Nuclear Energy University Program. DOE would support cost-shared, industry-led R&D for concept-level development and conduct research into high-temperature (HTR) reactor concepts, liquid metal cooled fast reactors (LMFRs), gas fast reactors (GFRs) and molten salt cooled reactors (MSRs). DOE will consider developing a test/demonstration reactor to further enhance its testing capabilities and support the timely deployment of advanced reactors. Finally, DOE will also pursue technical solutions to support the changing role of nuclear energy as part of a diverse electricity generation mix and for non-electric uses.

3.3 Strategic Objective 3: Support the development of fuel cycle pathways for advanced reactors

Working with industry to develop improved and advanced nuclear fuels is a major objective, both for existing LWRs and for the entire spectrum of advanced nuclear energy systems.
Developing advanced fuels is also essential to ensuring that sustainable fuel cycle options will be available in the future. Further R&D efforts in this area would focus on working with industry to develop accident tolerant fuels for LWRs and developing new fuels for advanced reactors, including tristructural-isotropic (TRISO) coated particle fuel, metallic fuel and transmutation fuels.



TRISO coated particle fuel

Recent research aimed at developing fuels for non-LWR advanced reactor systems has focused on qualifying TRISO-coated particle fuel and on investigating metal and long-term transmutation fuels. Activities have included irradiation testing, development of fabrication techniques, improvements in material testing capabilities, associated model development, and coordination with the Office of Nuclear Energy's nuclear model and instrument development programs. DOE is also cooperating with universities to support its advanced fuel development activities through the Nuclear Energy University Program.

Focus areas for DOE R&D in advanced, non-LWR nuclear fuels would include:

- Supporting advanced metal fuel development including demonstrating higher density, fuel burnup rates, and longer life fuels and fuel fabrication methods.
- Continuing the development of TRISO-coated particle fuel in support of fuel qualification.
- Examining potential liquid fuel options and development issues.
- Facilitating the regulation of advanced reactor fuel.
- Developing a baseline transmutation fuel.
- Advancing multi-scale physics modeling.

DOE's fuel cycle pathway would continue to adhere to proliferation resistance principles. Fuels would not include directly weapons-usable materials, non-accumulation of weapons-usable materials would be a criteria, diversion potential would be limited and the concept of security-by-design would be an expected element for facilities as well as the overall fuel cycle.

In addition to exploring new nuclear fuel options, DOE currently conducts R&D on the disposition of used nuclear fuel. This work aims to provide a sound technical basis for managing the back end of the nuclear fuel cycle, including the identification and evaluation of safe and secure options for used nuclear fuel storage, resource utilization, transportation, and permanent disposal of radioactive wastes. R&D on storage options currently focuses on closing technical gaps related to the extended storage of used nuclear fuel, including addressing uncertainties related to the performance of cladding for high-burnup used nuclear fuel and long-term canister integrity. Current R&D to address transportation issues is focused on ensuring the transportability of used nuclear fuel following extended storage, addressing data gaps regarding nuclear fuel integrity, assuring the retrievability of used nuclear fuel, and understanding stresses and strains during transportation. In the area of used nuclear fuel disposal, current R&D efforts are focused on identifying multiple viable disposal options and addressing technical challenges for generic disposal concepts in various host media. Overall R&D goals at this stage include reducing generic sources of uncertainty that may impact the viability of disposal concepts, increasing confidence in the robustness of generic disposal concepts, and developing the science and engineering tools needed to select, characterize, and license disposal options.

Supporting the Development of Fuel Cycle Pathways for Advanced Reactors

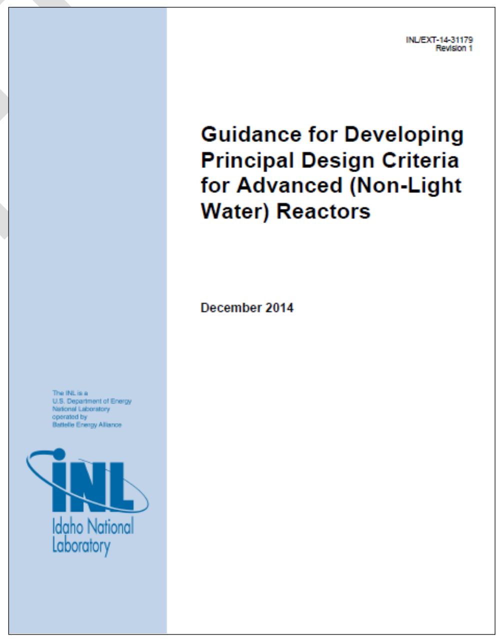
DOE will pursue R&D to develop improved fuels for existing reactor technologies and suitable fuels for advanced reactors. As informed by industry, these efforts will likely focus on TRISO-coated particle fuel for high temperature reactors, metallic fuel for fast reactors, and transmutation fuels for longer-term applications. DOE will also assess and pursue critical elements for the deployment of advanced fuel cycles, including identifying and characterizing fuels and separations/enrichment technologies. As part of these efforts, DOE would assess the need for and/or provide for the deployment of fuel cycle facilities. To address other aspects of the back end of the nuclear fuel cycle, DOE is pursuing R&D focused on the storage and disposal of used nuclear fuel. The aim of this R&D is to develop the technologies and capabilities needed to enable the safe storage, transportation, and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles, including identifying and addressing technical challenges that may arise from advanced nuclear fuel cycles.

3.4 Strategic Objective 4: Support the establishment of an efficient and reliable regulatory framework for advanced reactors

The NRC's framework of regulations, processes, and procedures for regulating the nuclear power industry is based largely on LWR technologies. For the last several years, DOE has been interacting with the nuclear energy industry to better understand its needs and priorities and better align DOE's R&D program to address those needs. Industry experts consistently point to the need for an appropriate, efficient and predictable regulatory framework as a high priority. This focus is consistent with Congressional intent as reflected in provisions of the Energy Policy Act of 2005 that pertain to the Next Generation Nuclear Plant (NGNP) project. These provisions direct the NRC and DOE to work together to develop an appropriate licensing strategy to support the deployment of next-generation technology. In a 2012 report to Congress on advanced reactor licensing,[7] the NRC described its overall long-term strategy for licensing advanced reactors and noted the need to better accommodate non-LWR technologies within the regulatory process. While the NRC has stated that the existing LWR-based regulatory framework, with appropriate exemptions, could in fact be utilized, establishing a regulatory framework for advanced reactors could offer significant benefits. Such a framework could more specifically address regulatory requirements for advanced reactors and make the review process more efficient and predictable. The NRC is in the process of developing a document that describes its overarching approach to preparing for non-LWR regulatory activities. That approach includes three major focus areas: technical preparations, licensing preparations, and outreach. It also includes enhancements to the regulatory framework for non-LWRs such as the development of advanced design criteria, the development of a staged licensing process, and early engagement with design-related policy issues

More recently, the NRC, with DOE's assistance, has begun developing a regulatory framework for advanced reactors. A goal of this effort is for the NRC to issue specific regulatory guidance on general design criteria for non-LWR advanced reactors by early 2017.

In September 2015, NRC and DOE held the first in a series of workshops to explore more efficient development and licensing processes for advanced reactors. The workshop series aims to explore options for increased efficiency, from both a technical and regulatory perspective, for safely developing and deploying advanced non-light water reactors. The discussions will cover both near- and longer-term opportunities to develop new concepts and enhance appropriate regulatory processes and guidance.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Revision 1

Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors

December 2014

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

INL
Idaho National Laboratory

DOE and NRC have agreed to continue to address action items identified at the first workshop and will provide updates during subsequent meetings. Other ideas to be considered include issuing topical reports to obtain feedback on specific technical or analytical issues for less mature reactor concepts, developing an informal preliminary licensability review process, and addressing the need for modifications to existing licensing guidance, such as the Standard Review Plan, to address differences associated with advanced reactors.

[7] http://www.nrc.gov/reading-rm/doc-collections/congress-docs/correspondence/2012/frelinghuysen-08-22-2012.pdf

Supporting the Establishment of a Regulatory Framework for Advanced Reactors

DOE and its stakeholders will collaborate with the NRC as the NRC develops a regulatory framework for advanced reactors. This collaboration could include efforts to provide assistance to the NRC as it develops design criteria for advanced reactors, staged licensing processes, and preliminary licensability review processes. In addition, DOE will assist the NRC in efforts to resolve key policy issues, co-host joint workshops, explore options for new fuel and fuel fabrication facilities, and modify existing guidance (such as the Standard Review Plan) to accommodate advanced non-light water reactor designs.

3.5 Strategic Objective 5: Maximize the effectiveness of public and private sector investments and explore policy incentives to aid the private sector in accelerating advanced reactor deployment

While industry will lead development and deployment efforts, the high cost of designing a nuclear plant can challenge the ability of reactor vendors to develop new designs and the ability of electric utilities to deploy new reactors. DOE could use public-private partnerships and various financial mechanisms to address cost barriers to advanced reactor development and deployment. Past DOE efforts to support the deployment of new nuclear technologies have included initiatives such as the Nuclear Power 2010 program, which supported site identification and first-of-a-kind engineering for Generation III+ light water reactor designs. It also implemented certain financial incentives, authorized under the Energy Policy Act of 2005, for building new nuclear power plants. The SMR Licensing Technical Support Program also provided support for reactor deployment.

Public-private engagement is an important element in any future deployment strategy for advanced reactors. In addition to interacting with the public through various forums, DOE participates in stakeholder meetings, provides information, and solicits input on issues such as reactor regulation, siting, and used fuel disposition. Mechanisms for accelerating the deployment of advanced reactor technology include public-private partnerships, technology centered working groups, and policy and financial incentives.

Public-private partnerships could be used to develop and commercialize specific elements of advanced reactor technology as well as to finance the overall design, licensing, and construction of commercial plants. DOE has been funding cost-shared, industry-led R&D for technology development projects, cost-shared programs for developing reactor concepts, and the Small Business Innovation Research program, which provides federal seed money to domestic businesses to engage in research that has the potential for commercialization. In addition, DOE's Office of Technology Transitions (OTT) has launched the statutory Technology Commercialization Fund. This fund provides an additional mechanism for matching private funds with Federal funds in support of efforts to commercialize promising energy technologies developed by the DOE national laboratories. Going forward, DOE will explore the use of public-private partnerships—similar to the public-private partnerships utilized in the Nuclear Power 2010 and SMR Licensing Technical Support programs—to address the need for licensing technical support and construction support. These types of partnerships could help to advance non-LWR reactor designs that are relatively mature and support deployment in the early-2030s timeframe. Finally, OTT's new Clean Energy Investment Center provides the capability to bring additional partnering services and access to the investment community in support of future commercialization efforts.

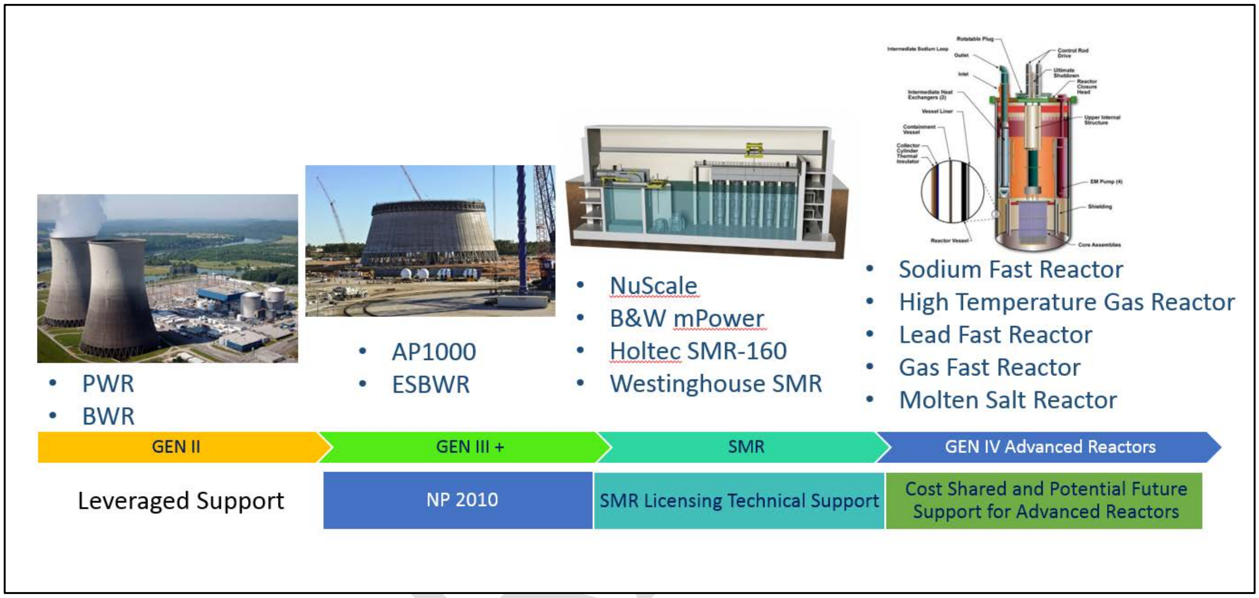

Figure 4. Public-Private Partnerships for Reactor Development

<u>Technology centered working groups</u> can bring together vendors who are working on reactor concepts that have much in common. For instance there are many vendors working on sodium fast reactors, high temperature gas reactors, molten salt cooled reactors, and other advanced reactor concepts. One idea to accelerate development is for these vendors to pool resources as appropriate and work on technical, regulatory, safety, security, and nonproliferation issues in a collaborative manner. DOE could play a role in helping to organize such groups, consistent with applicable law. Technology centered working groups, in turn, could help DOE identify the government investments that would benefit the greatest number of vendors and utilities.

<u>Policy and financial incentives</u> can be used to accelerate private investment in advanced nuclear technologies. Interest in such incentives has been growing, particularly in the broader context of pursuing policy initiatives that reduce carbon emissions and promote low-carbon energy sources. Financial incentives can be tailored to encourage investment in technologies that are still in the early, proof-of-concept development phase as well as technologies that have reached the construction or production phase. In 2014, for example, DOE provided $12.5 billion in federal loan guarantees for the construction of two large new nuclear reactors under the Title 17 loan guarantee program.

Power purchase agreements are another mechanism for addressing cost barriers. Such agreements allow nuclear generators to sell electricity at a fixed price for a specified period of time, thereby guaranteeing a certain level of revenue, reducing market uncertainty, and encouraging further deployment.

Another approach is for the federal government to act as the “first mover” on new reactor projects by partnering with power companies or utilities to enter into negotiated ownership arrangements in which the facility is eventually purchased by the private-sector partner. The nuclear units would be licensed, built and operated by the private-sector partner.

Finally, production or investment tax credits can also be used to support the deployment of new nuclear power technologies.

Maximizing the Effectiveness of Public/Private-Sector Investments to Accelerate Advanced Reactor Deployment

DOE will explore new ways to work with the private sector to accelerate advanced reactor deployment and support the further development of selected advanced reactor concepts. DOE would also use public-private partnerships and technology-specific working groups to identify opportunities for government investment that could help advance multiple reactor concepts. Finally, DOE and the Administration will explore the use of other appropriate policy or financial incentives to support advanced reactor deployment.

3.6 Strategic Objective 6: Address human capital and workforce development needs

The adequacy of the nuclear energy workforce is a growing concern for the nuclear energy industry and an issue of obvious importance for future efforts to deploy new nuclear technologies. According to recent estimates by the Nuclear Energy Institute, 39% of the U.S. nuclear workforce will be eligible for retirement by 2018. This means that the industry may need to hire 20,000 new workers over the next several years to replace retiring workers. More broadly, investments in a skilled workforce are needed to ensure that the nation can continue to build, maintain, and operate a reliable and efficient energy infrastructure. Historically, a large part of this investment has come through federal funding for education and research.

Since FY09, NEUP has awarded $374.2M to 94 schools in 39 states and the District of Columbia.

DOE's Office of Nuclear Energy created the Nuclear Energy University Program (NEUP) in 2009. NEUP engages U.S. colleges and universities to conduct R&D, enhance infrastructure, and support student education, thereby helping to sustain a world-class nuclear energy and workforce capability. It has funded research projects in areas that are relevant for the development of components and materials for advanced nuclear reactors. This funding not only supports the development of new reactor concepts, it also attracts students to enter nuclear energy and related nuclear science fields.

At the direction of Congress, the Department also supports workforce development by funding annual undergraduate scholarships and graduate-level fellowships in nuclear energy-related fields of study through the Integrated University Program (IUP). Since the awards were initiated in 2009, 98% of students who completed these fellowships subsequently pursued additional education or careers in nuclear energy fields at the Department's national laboratories, government agencies, academic institutions, or private companies.

Developing the Nuclear Energy Workforce of the Future

DOE plans to continue funding nuclear-related research projects and scholarships and fellowships through its Nuclear Energy University Program (NEUP) and Integrated University Program (IUP), respectively. In addition, DOE will promote advanced reactor technology training opportunities through workshops, curriculum development, and joint laboratory, university, and industry projects. DOE will also seek opportunities to engage academic institutions, where appropriate, in enhancing research efforts relevant to the development of advanced reactor technologies.

4. Conclusion

DOE's strategy for the development and deployment of advanced nuclear reactors includes specific objectives for improving experimental and test capabilities and expanding access to facilities and expertise, retiring technical risk, developing fuel cycle pathways, assisting the NRC in efforts to establish an advanced reactor regulatory framework, effectively maximizing private sector resources to accelerate deployment, and addressing human capital and workforce development needs. Implementation of the activities associated with these objectives would need to be coordinated and sequenced to assure that federal efforts produce the desired outcomes. Activities must be prioritized and resources allocated to deliver the right solution, at the right time, to the right customer.

Because the development needs of individual advanced reactor concepts vary considerably, all elements of this strategy may not apply to all concepts. However DOE intends this Vision and Strategy to guide programmatic efforts in support of initiatives for the development and deployment of at least two advanced reactor concepts in the early 2030s.

Improving DOE infrastructure and facilitating access would have benefits for most technologies and concepts. Efforts to reduce technical risk are intended to both address specific technical issues and to advance concept maturity. DOE support for the development of at least two new reactor concepts is not intended to down-select technology areas; rather, it is intended to demonstrate that further funding can advance specific concepts while also showing that advanced reactors are making viable progress toward being able to address the nation's clean energy needs. DOE expertise and infrastructure would assist the NRC in its efforts to establish a regulatory framework that makes for effective and efficient license submission and subsequent NRC review processes. Fuel cycle work would include developing specific fuels for longer-term concepts and exploring fuel disposition for advanced reactors. Efforts to maximize the effectiveness of public and private sector investments and develop human capital with expertise in non-light water reactor technologies are likewise essential to accelerate advanced reactor deployment and to ensure that the talent needed not only to develop, but also operate these new reactors is available in the future.

While elements of this strategy could support reactor concepts at differing levels of development, DOE has formulated a notional timeline for completing the design process and submitting license applications to the NRC for reactor concepts that could be in a position to reach milestones in the near term (see next page). More time would be needed to address design, fuel, materials or component development challenges for other, less mature reactor concepts. DOE could support certain development needs for some of these longer-term concepts. DOE would also continue to engage in joint efforts with nuclear industry organizations to pursue shared objectives in the development and deployment of advanced reactors.

Timeline for Advanced Reactor Development and Deployment

DOE has initiated a multi-faceted effort to support the design and licensing of at least two commercial advanced reactor concepts by the early 2030s. This effort includes working with the NRC and with DOE's stakeholders and industry partners as the NRC develops a new regulatory framework for advanced reactors. Current plans target the completion of general design criteria for advanced reactors in 2017. The NRC expects early engagement with potential applicants on any policy issues related to licensing so that there is a timely resolution before an application would be submitted. Throughout this period, research and development aimed at retiring technical risks associated with fuels, materials, and components would continue. Through GAIN, DOE expects to enhance the nation's nuclear innovation infrastructure and improve industry's access to DOE capabilities and expertise. The TREAT reactor is scheduled to go on line in 2018. Additionally, DOE's cost-shared support for further development of two advanced reactor concepts, launched in 2015, is expected to continue *through 2020. Meanwhile, DOE's test/demonstration reactor study, to be completed in 2016, should provide further options for supporting future reactor commercialization with the expectation that a potential new test or demonstration reactor would be operational by the late 2020s if needed.*

REFERENCES

ACRONYMS

ABWR	Advanced Boiling Water Reactor
AEC	Atomic Energy Commission
ALWR	Advanced Light Water Reactor
ASME	American Society of Mechanical Engineers
ANS	American Nuclear Society
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
COL	Construction and Operating License
DAS	Deputy Assistant Secretary
DBA	design basis accidents
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy-Idaho Office
EIA	Energy Information Administration
EOI	Expression of Interest
EPRI	Electric Power Research Institute
ESP	Early Site Permit
FY	fiscal year
GEN III+	Generation III+
GHG	greenhouse gas
GWe	gigawatt electrical
HCSG	helical coil steam generators
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
INPO	Institute of Nuclear Power Operations
ITAAC	inspections, tests, analyses, and acceptance criteria
INL	Idaho National Laboratory
IPSR	Integral Primary System Reactor
LWR	light water reactor
MWh	megawatt hour
MT	metric ton
NDE	non-destructive examination
NE	Office of Nuclear Energy
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NESCC	Nuclear Energy Standards Coordination Collaborative
NGNP	Next Generation Nuclear Plant
NIST	National Institute of Standards and Technology
NP2010	Nuclear Power 2010
NRC	U.S. Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
OTT	Office of Technology Transitions
PIRT	Phenomena Identification and Ranking Table

PRA	probabilistic risk assessment
PRDP	Power Reactor Development Program
PSA	probabilistic safety assessment
R&D	research and development
RD&D	research, development, and demonstration
SDO	standards developing organization
SMR	small modular reactor
SSC	structure, system, and components
U.S. NIC	U.S. Nuclear Infrastructure Council