FAS

Moving Advanced Nuclear Energy Systems to Global Deployment

A special report published by the Federation of American Scientists

Charles D. Ferguson
August 2015

About FAS

Founded in 1945 by many of the scientists who built the first atomic bombs, the Federation of American Scientists (FAS) is devoted to the belief that scientists, engineers, and other technically trained people have the ethical obligation to ensure that the technological fruits of their intellect and labor are applied to the benefit of humankind. The founding mission was to prevent nuclear war. While nuclear security remains a major objective of FAS today, the organization has expanded its critical work to address urgent issues at the intersection of science and security.

FAS publications are produced to increase the understanding of policymakers, the public, and the press about urgent issues in science and security policy. Individual authors who may be FAS staff or acknowledged experts from outside the institution write these reports. Thus, these reports do not represent an FAS institutional position on policy issues. All statements of fact and expressions of opinion contained in this and other FAS Reports are the sole responsibility of the author or authors.

About the Author

Charles D. Ferguson is the President of the Federation of American Scientists. Prior to FAS, Dr. Ferguson served as the Philip D. Reed Senior Fellow for Science and Technology at the Council on Foreign Relations (CFR). Before his work at CFR, he was the Scientist-in-Residence in the Monterey Institute's Center for Nonproliferation Studies, where he co-wrote (with William Potter) the book *The Four Faces of Nuclear Terrorism* (Routledge, 2005). He was the lead author of the 2003 report *Commercial Radioactive Sources: Surveying the Security Risks*, which was the first in-depth, post-9/11 study of the "dirty bomb" threat. This report won the 2003 Robert S. Landauer Lecture Award from the Health Physics Society. He has served as an adviser to the U.S. government and national laboratories. In May 2011, his book *Nuclear Energy: What Everyone Needs to Know* was published by Oxford University Press. In 2013, he was elected a Fellow of the American Physical Society for his work in educating the public and policy makers about nuclear issues. He graduated with distinction from the U.S. Naval Academy, served in the nuclear Navy, and earned a Ph.D. in physics from Boston University.

For more information about FAS or publications and reports, please call 202-546-3300, e-mail fas@fas.org or visit www.fas.org.

Design, layout, and edits by Allison Feldman.

Cover Photo: © franckreporter, iStock by Getty Images.

Purposes of this Report

This report was written by a senior analyst with the Federation of American Scientists, a non-governmental organization working to provide science-based analysis for solutions to energy security and international security. Energy security is defined here as *ensuring secure supplies of energy sources at costs that consider economic development and environmental impact*. Understanding the impact of nuclear power on international security involves assessment of the potential for proliferation of nuclear weapons programs.

With this wider lens of security, economic, and environmental interests, this report identifies the major factors that will affect deployment of advanced reactors in the coming years to decades and analyzes what industry and governments need to do to move forward toward the ultimate goal of widespread deployment of potentially hundreds of highly energy efficient, much safer, more proliferation-resistant, and economically competitive nuclear power systems. Moreover, the report looks at lessons learned from the history of development and deployment of *Generation II* and *III* reactors and seeks to learn explicitly about the reasons for the predominant use of light water reactors. It then seeks to apply these lessons to current efforts to develop advanced nuclear energy systems. In the process of that assessment, the report reviews the status of the global cooperative and national efforts to develop and eventually deploy advanced nuclear energy systems. The main intentions of the report are to provide a guide to policymakers in the form of findings that lay out potential pathways to forward deployment of one or more advanced nuclear power systems within the next ten to twenty years.

Table of Contents

Executive Summary: Up-Front Findings and Guideposts 4

Introduction: Advanced Nuclear Energy and Its Role in Helping Alleviate Global Climate Problems and Energy Needs 6

Lessons Learned from the History of Light Water Reactor Development: The Roles of Government and Vendors, Utility Risk-Aversion, and Technological Lock-In 9

- *How and Why LWRs Dominated the Nuclear Power Industry in the United States* 11
- *Concerns about Technological Lock-In* 15

Lessons Learned from the Accidents at Three Mile Island and Chernobyl: The Need for Passive and Inherent Safety Systems 17

A New Millennium and a New Era for Nuclear Power: The Creation of the Generation IV International Forum and Its Roadmaps 19

- *Gas-Cooled Fast Reactor (GFR)* 21
- *Lead-Cooled Fast Reactor (LFR)* 23
- *Molten Salt Reactor (MSR)* 24
- *Sodium-Cooled Fast Reactor (SFR)* 27
- *Supercritical-Water-Cooled Reactor (SCWR)* 28
- *Very-High-Temperature Reactor (VHTR)* 29
- *GIF's Working Groups* 30
  - Economic Modeling Working Group 30
  - Risk and Safety Working Group 31
  - Proliferation Resistance and Physical Protection Working Group 31

Small is Attractive: Why there is Renewed Interest in Small, Modular Reactors 33

Regulatory Requirements for Licensing and Constructing Advanced Nuclear Energy Systems 35

Knowledge Management, Knowledge Creation, and Training of the Workforce 37

Conclusions: What Needs to be Done for Making Further Progress? 39

Executive Summary: Up-Front Findings and Guideposts

General Principles

- Energy efficiency in all (nuclear and non-nuclear) power systems will become increasingly important because these systems will tend to optimize use of resources and tend to save on fuel and operating costs.

- Safer nuclear plants matter for public acceptance and tend to result in better power performance. But the layering of more and more active safety systems has tended to drive up nuclear power plants' costs. Consequently, shifting toward plants that do not depend on operators' intervention to maintain safety can offer much greater safety at potentially lower cost. Some advanced plant designs are considered "walk-away-safe," and some *Generation III* and *III+* designs make significant use of "passive" safety systems based on concepts that do not require operator activation, such as the use of natural convection systems to circulate coolant in an emergency.

- While nuclear power plants have traditionally generated constant full power, known as *base load power*, newer systems that can work in load following or peaking power modes could be more competitive especially in merchant-based utility systems in which electricity prices can fluctuate dramatically throughout a 24-hour period, as well as seasonally.

Role of Industry

- Modular construction practices would likely result in cheaper capital costs because of the capability to mass produce components and assemble them uniformly. In the past, many plants have had unique design features that have driven up costs and have impeded learning from mass production. Small modular reactors' designs, in particular, promise such learning and concomitant cost reductions.

- Advanced nuclear energy systems that can provide services in addition to electricity generation can offer several commercial advantages. These services include hydrogen production for fuel cells, steam production for industrial processes, and seawater desalination.

- Newer and largely unproven fuel systems will face substantial commercial hurdles and skepticism in the utility industry as well as face longer evaluation periods in regulatory agencies.

Regulatory Issues

- Regulatory streamlining could allow for newer plants to obtain licenses without waiting years for the approval process. However, regulatory authorities have become used to regulating light water reactor systems and will need sufficient time, staffing, and technical resources to regulate newer and more advanced systems that are significantly different in design and concept from traditional systems.

- Regulatory agencies have considerable work to do and have need of substantial human and technical resources to prepare for licensing applications of advanced nuclear energy systems especially those that do not use light water reactor technologies.

Role of Governments

- Government funding will be needed for the first demonstration reactors and commercial deployments. Utilities are risk averse and will not want to spend potentially billions of dollars on new technologies.

- Small, modular reactors, which have power ratings one third or less than a typical commercial power reactor, could help address the high capital cost hurdle because an SMR is not expected to cost much more than a billion dollars for many of the proposed designs. However, these systems, especially those that are different than the light water reactors, are largely unproven, certainly at the commercial prototype level. Thus, utilities will continue to be risk-averse in buying the first SMRs without substantial government support. While the U.S. Department of Energy has offered some tens of millions in such support, this might not be sufficient. A government or governments may need to invest a few billion dollars or more to test out the first SMRs on a commercial scale.

- Bilateral and multilateral partnerships will need to be strengthened to increase the likelihood of successful development and deployment of advanced nuclear energy systems. Governments of major nuclear energy producing nations such as the United States, China, France, Republic of Korea, Japan, India, Russia, and the United Kingdom should foster these partnerships and commit adequate financial and technical resources to these initiatives.

Introduction: Advanced Nuclear Energy and Its Role in Helping Alleviate Global Climate Problems and Energy Needs

According to numerous leading climate scientists, the world's climate is undergoing human-induced changes due to massive emissions of greenhouse gases from burning of fossil fuels and deforestation.[1] These climatic changes appear to put the planet on a collision course for a sixth global extinction of numerous species, consequent loss of biodiversity, rising sea levels that threaten to flood island nations and mega-cities along the coasts, and massive effects on agriculture and the global food supply.[2] Meanwhile, the global population has recently surpassed seven billion people, and many demographers forecast more than nine billion people by mid-century. Most of this population growth will happen in the developing world, which by definition, is attempting to increase its economy to improve the standard of living of its people.

This growth drives up demand for more energy resources, particularly greater access to, and use of, electricity. According to the International Energy Agency and the World Bank, 1.2 billion people do not have access to electricity. The United Nations has set the ambitious goal to shrink this gap to essentially zero people without electricity by 2030. The depressing news is that the "rate of growth in electrification has still been slower than population growth (Access to electricity grew at about 1.2 percent per year between 1990 and 2010, while the global population grew at 1.3 percent per year.)"[3] South Asia and Sub-Saharan Africa are the two regions most lacking in electricity generation.

"Business as usual" methods will result in more than one billion people still without electricity indefinitely into the future. Moreover, the problems of climate change will exacerbate if business as usual trends lead to more burning of dirty fossil fuels. Coal still remains abundant in many nations around the world, especially in China and India, the two with the largest national populations and two of the most rapidly developing nations. Cleaner fuel sources, such as nuclear energy and renewable energies including solar and wind, are available but collectively fill a minority share of the globe's electricity needs at about 16 percent in 2014 with 12 percent from nuclear and about 4 percent from wind and solar.[4] Fossil fuel sources provided about 70 percent of the world's electricity in 2014. (An

---

[1] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, R.K. Pachauri and L.A. Meyer, eds.). IPCC, Geneva, Switzerland, 151 pp.

[2] See, for example, Elizabeth Kolbert, *The Sixth Extinction: An Unnatural History* (New York: Henry Holt and Company, 2014).

[3] Brad Plumer, "Here's Why 1.2 Billion People Still Don't Have Access to Electricity," *Washington Post*, May 29, 2013, which bases its reporting on the International Energy Agency and World Bank's assessment reports.

[4] Notably, hydropower, which many people consider renewable or at least not a major contributor to greenhouse gas emissions, supplied about 16 percent of global electricity in 2014, but social and environmental concerns about dams have severely limited the further expansion of hydropower with many dams having to shut down although run-of-the-river-

operating nuclear power plant does not emit greenhouse gases, and solar and wind electricity sources do not either, although the entire life cycle of nuclear, solar, and wind energy systems do generate relatively small portions of such emissions but at much lower rates than fossil fuel energy systems.) To generate enough power for the more than one billion people lacking electricity and to displace coal and other fossil fuels where electricity is being generated, nuclear, solar, and wind energy systems need to be deployed at a much greater scale.

While solar and wind energy systems will play larger roles in the coming years to decades, this report examines the near (up to ten years) to long term (ten to thirty years) roles for advanced nuclear energy systems because of the huge energy density available from nuclear energy that can be especially well suited to providing massive amounts of cleaner energy to urban dwellers. As of 2014, a majority of the world's population lives in cities, and the relative proportion of city dwellers is expected to outpace rural residents in the coming decades. Although people in cities can and generally do use renewable energy systems, people in high-rise apartment buildings, for example, would have difficulty in having their own solar panels or wind turbines.[5] Most electrical power would be distributed to these people from power plants outside the cities. While these plants could include concentrated solar thermal plants and wind farms stretching over hundreds of miles, nuclear power plants could provide reliable power for all weather conditions around the clock while still having a much smaller "footprint" in land area use as compared to renewable energy sources.

But can nuclear power take the leap from about 12 percent of the world's current electricity generation to a much larger share? To make a greater contribution to the globe's energy supply, nuclear energy will have to be financially competitive while also providing reliable and safe means of electrical power. As discussed in this report, the economic experience has, at best, had mixed results for the costs of nuclear power plants. In general, the capital costs for construction have been high while the operating and fuel costs have been comparatively low, as compared to coal-power plants. The relatively cheap prices in recent years for natural gas in the United States, for example, have further made nuclear power appear economically uncompetitive in many regions. But natural gas will not last forever; shortages may be experienced in the coming decades based on demands placed on this fossil fuel. Also, the low prices are not guaranteed to stay low.

Presently, almost all operating nuclear power plants are generally referred to as *Generation II* designs, which came from developments in the late 1950s to the 1970s and were mostly built until the late 1980s. *Generation II* designs are typically of two types: *pressurized water reactors* (PWRs) and *boiling water reactors* (BWRs), which both use light water, or H2O, to moderate neutrons to keep the nuclear chain reaction going and to cool the reactor core. The LWRs usually have energy efficiencies of about 33 percent in conversion of the reactor's heat to useful electricity.

---

hydro power is typically more environmentally friendly but may not generate as much electricity as large dams.

[5] For example, the author has solar panels on his row house in Washington, DC, to provide about half of his home's electricity on average annually, and still makes use of nuclear generated electricity from the Calvert Cliffs Nuclear Power Plant in nearby Calvert County, Maryland.

In the past twenty to twenty-five years, *Generation III* and *III+* designs have started to be developed and deployed. These systems are evolutionary designs to improve primarily on the *Generation II* LWRs with added safety features but are usually not much improved in terms of energy efficiency. Advanced nuclear energy systems are mostly considered to be so-called *Generation IV* designs, which were first classified as such around the year 2000 (as described later in this report). Many *Generation IV* designs have their roots in the 1950s and 1960s, as this report will describe. Several of the *Generation IV* designs are significantly different in concept than *Generation II*, *III*, and *III+* and typically have much greater energy efficiencies of about 40 to 50 percent. Technological improvements in recent years and the near to intermediate future could make some of these *Generation IV* designs commercially viable in the not too distant future. But they will have to compete with the currently available *Generation III* and *III+* designs as well as the relatively cheap coal-fired and natural gas-fired power plants.

Being more energy efficient than presently operating nuclear power reactors, advanced nuclear energy technologies hold tremendous potential to make much further contributions to help solve the world's energy needs and help reduce the emissions of greenhouse gases to the atmosphere. While many countries have demonstrated significant progress on research and development, several financial roadblocks have impeded full deployment of these technologies. The real test is the commercial market. As underscored by Dr. Andrew Sowder, senior technical leader at the Electric Power Research Institute (EPRI), "It is great to develop a technology, but it's really not commercially viable unless you can license it and someone can provide the money to finance it."[6] [EPRI is a nonprofit organization focused on providing near and long term solutions for the electric power industry and the industry's customers.]

---

[6] "ANS Winter Meeting, Nuclear: The Foundation of Clean Energy," *Nuclear News*, January 2015, p.67.

Lessons Learned from the History of Light Water Reactor Development: The Roles of Government and Vendors, Utility Risk-Aversion, and Technological Lock-In

This section takes a brief but relatively in-depth look at the history of nuclear power to glean lessons relevant for the future development of advanced nuclear power systems. In the late 1940s, after the Second World War, peaceful nuclear power was in its infancy. The Manhattan Project harnessed nuclear energy for the purposes of making nuclear weapons, and this also led to early work on the first types of nuclear reactors. However, these reactors were geared toward production of weapons-grade plutonium and not for electricity generation.

By the end of the war, leading nuclear scientists were already starting to think about and plan for the peaceful applications of nuclear power. Because available data at that time indicated that uranium resources were scarce, these experts believed that nuclear power's viability required *breeder reactors*. Breeder reactors create more fissile material than they consume by using the excess neutrons from fission to breed more fissile material from fertile material. For example, fission of a fissile uranium-235 nucleus creates more than two, but not more than three, neutrons. One of the neutrons is used to further fission with another uranium-235 nucleus while the excess neutrons can be absorbed by uranium-238 nuclei, which are also fertile. After two radioactive decays, the material is transformed into plutonium-239, a fissile material. Thus, more plutonium-239 can be produced than the uranium-235 that underwent fission. This plutonium-239 can be recycled into new fuel for reactors. The important point here is that from the early days of nuclear energy development, leading scientists were working on designs for breeder reactors on the assumption that this was needed to make nuclear energy viable for decades to come.

In a parallel effort in the late 1940s and into the early 1950s, the United States launched a program to make nuclear reactors suitable for submarines. Submarines are relatively compact warships designed to dive hundreds of meters under the surface of the seas and to withstand intense shocks from underwater explosions. The Navy wanted to deploy submarines for months at a time without the need for refueling. These boats had to be quiet and stealthy in order to reduce the likelihood of detection from an enemy's anti-submarine warfare techniques. Thus, nuclear reactors for submarine propulsion had to be rugged, quiet, fit in small compartments, and reliable over many years (and ideally decades). Then-Captain and later Admiral Hyman Rickover became the leader of the naval nuclear propulsion program. He and his team of engineers had studied many different reactor designs at Oak Ridge National Laboratory as well as had sought advice at other prominent U.S. laboratories. He was famous for stating that he learned from studying technologies where one should not choose the very "best" technology because that would be too risky, especially for such a demanding environment as undersea warfare. However, he also was very reluctant to choose the "second best" technology. Instead, he chose what some would have considered the "third best" technology: light water reactor technology. It might be deemed "third best" because it was not very energy efficient but still efficient enough at around 33 percent for modern light water reactors.[7] It was also not suitable, or at least optimal, for breeding new

---

[7] Norman Polmar, *Rickover: Father of the Nuclear Navy* (Potomac Books, 2007).

fissile material, although light water reactors using low enriched uranium fuel do derive much of their energy over their operating life from producing and fissioning plutonium.

The advantages of light water reactors were apparent for seagoing vessels and for a navy that had considerable experience with steam-powered boilers. One advantage was that the relatively low efficiency reactors had a ready heat sink in the surrounding sea. The U.S. Navy also had access to a growing stockpile of highly-enriched uranium (HEU) as a by-product of the nuclear weapons program. Giant gaseous diffusion plants were used to enrich many hundreds of metric tons of HEU. HEU is very energy dense and the Navy eventually used reactors designed for weapons-grade uranium with more than 90 percent enriched in uranium-235.

While Rickover had the Office of Naval Reactors design and build two sodium-cooled reactors, the *S1G* followed by the *S2G*, he was very dissatisfied with that reactor because of the difficulty in operating it and the concerns about the reactivity of liquid sodium with air and water. This experience further solidified Rickover's decision to stick with the simpler system of a pressurized water reactor. Liquid water under high pressure has good heat transfer properties and can be relatively easy to use in generating steam for propulsion in turning the propeller of the submarine and creating electricity in the turning of the turbines used to operate the electric generator. Consequently, because of the U.S. Navy's determination to have a nuclear-powered submarine by the mid-1950s, PWR technology received a significant "head start" in operational experience over several other competing designs (although R&D continued on other designs such as gas cooled reactors and molten salt reactors).

LWRs gained another major boost as a result of President Dwight Eisenhower's Atoms for Peace initiative, launched in December 1953. The United States sought to win the upper hand in the "peace" race with the Soviet Union by showing the world that U.S. nuclear technologies were not just for weapons or for other military purposes, but could, and would, improve the quality of life for humanity through applications of nuclear energy to agriculture, medicine, and electricity generation. In the latter area, the United States needed to urgently showcase a commercial power reactor. Because of the lead development of the PWR, it was chosen as the first major commercial development project at Shippingport, Pennsylvania, although early research at some national laboratories had shown the potential promise of alternative reactor technologies. The United States also moved quickly to change its federal law via the 1954 Atomic Energy Act to allow sharing of "atomic energies" with other countries through peaceful nuclear energy cooperation agreements. This led to many client states receiving research reactors and subsequent support for power reactor development. These power reactors mostly used LWR technology (with some exceptions being *pressurized heavy water reactors* (PHWRs) or CANDUs developed and exported by Canada).

How and Why LWRs Dominated the Nuclear Power Industry in the United States

In 1977, the RAND Corporation published the findings of a comprehensive study of why LWRs seized such a strong hold on the nuclear power industry.[8] The authors cautioned that the history is not neat and simple; there are overlapping themes, issues, and factors. They underscored that there is not a "nuclear industry" as such: "The phrase encompasses an amalgam of risk-averse utilities, scientists and engineers dedicated to advancing the state of the nuclear technology, regulatory bodies concerned with the cost of electricity to the consumer, plant operators impatient of demands for ever more extensive safety precautions, and interveners convinced that catastrophe is imminent, reactor manufacturers concerned with their sales prospects, and major or minor participants in abundance with roles that extend from extracting uranium to keeping an existing plant 'on line' at all possible times."[9]

Notably, the U.S. national goal for nuclear energy since 1953 was to make it cost competitive with electricity generated by the burning of fossil fuels, in particular, coal-fired power plants. In 1977, when the RAND researchers were writing their report, it was highly uncertain whether nuclear power plants could compete economically with fossil fuel power plants even with an upward trend in fossil fuel prices between 1967 and 1977. High construction costs and continual changes in safety regulations were two major contributing factors.

In the RAND report's findings, the analysts pointed out that "more than five principal avenues to commercially competitive nuclear power seemed open in the early 1950s, but 20 years later the LWR was the only healthy survivor." In the late 1950s, the Atomic Energy Commission (AEC) sponsored a comprehensive Power Reactor Development Program in order to not rely on one particular technology and allow for evaluating different design concepts for commercial viability. But as the RAND report notes, some critics have complained that the AEC may have pulled R&D support prematurely from some of these alternative technologies, most notably the high temperature gas reactor (HTGR), which proponents have emphasized to be safer and more energy efficient than the LWR. Another critique is that the AEC "elected to solicit the support of small utilities for reactor technologies far riskier than the LWR" and that these utilities did not have adequate financial wherewithal to risk on these alternatives. In contrast, the LWRs' "head start" enabled them to demonstrate their reliability in a relatively brief period of the late 1950s to early 1960s. Nonetheless, utilities were not willing to gamble on LWRs without subsidies from government or vendors.

Government, mostly via the AEC, provided large subsidies in the late 1950s and into the early 1960s. But "the utilities remained fearful that unless privately funded commercial-scale nuclear plants were built, the government might in the end decide to fund something on the order of a nuclear TVA." TVA, or the Tennessee Valley Authority, was founded in 1933 during the Great Depression as a massive public works program that the federal government funded and owned in order to provide electricity, flood control, navigation, and economic development to the Tennessee Valley region of the southern United States, an area hit hard by the Great Depression. After the Great Depression, executives of U.S. utilities wanted

---

[8] Robert Perry et al., "Development and Commercialization of the Light Water Reactor, 1946-1976," R-2180-NSF, RAND, June 1977.

[9] Ibid, p. vi.

much less or even no government involvement or ownership in their businesses. But to make nuclear power plants cost-competitive with fossil fuel plants, their capital costs would have to be kept comparable to coal-fired plants. However, with only a few government-subsidized nuclear plants as a guide, it was highly uncertain that nuclear plants could compete in the unsubsidized market.

The financial innovation was for vendors to offer "turnkey plants," meaning the companies building the plants would guarantee a fixed price and would have to pay for any cost increases that might occur during construction. Only two companies, Westinghouse and General Electric, had the financial depth at that time to risk making this offer. While the total amount of losses were not reported by these companies, both lost an estimated more than $1 billion over a several year period on these nuclear construction projects that they started in the 1960s. The RAND report noted that there was "unrealistic expectations of cost competitiveness" as compared to fossil fuel-fired plants. Why did this occur? Aside from the fact that nuclear power plants were in their infancy, vendors believed that "large nuclear plants were merely enlarged copies of the smaller plants with which the industry had all its pre-1960 experience."[10] Another misconception was that the nuclear power plants could be built in a similar fashion as coal-fired power plants and that the "nuclear heat source could be treated as a variant of a conventional steam generator. This proved to be far from the case. The consequences were vastly greater construction costs than had been expected and considerable delays in plant construction." Among the technical reasons why, "requirements for precision fitting and for fail-free equipment were considerably more demanding for nuclear installations than for older fossil-fuel plants, and the difficulties of satisfying demands for high safety standards accounted for many of the cost and schedule overruns that marked the 1970s."[11]

By 1963, some utility executives thought they could order non-turnkey plants because they believed that if their companies had control over contracting and scheduling, the costs could be much better contained. However, they too experienced major cost overruns and construction delays. Both turnkey and non-turnkey plants suffered from significant estimating errors for the costs. The financial losses could have dealt an irreparable blow to a nascent industry given the opposition by the mid-1960s at GE and Westinghouse to continue to offer turnkey contracts. Instead, they increased their bid prices. Nonetheless, some utilities persisted in investing in nuclear plants after the mid-1960s although they were experiencing significant cost increases.

The mounting financial costs might have halted further construction if other elements of world finances had not changed and made nuclear power still look somewhat competitive. Namely, coal prices increased after 1965. Moreover, the burgeoning environmental movement in the United States became increasingly alarmed by how burning of coal resulted in harmful health effects. By the early 1970s, this movement resulted in the passage of the National Environmental Policy Act and the creation of the Environmental Protection Agency. Regulatory rule changes required coal plants to make design changes to cut down on emissions of harmful substances such as mercury and heavy metals. By the 1980s, the focus would turn to sulfur dioxide and nitrous oxide, chemical compounds that result in harmful

---

[10] Ibid, p. 83.

[11] Ibid, p. 83.

acid rain. Today, the focus of EPA rule changes is on limiting emissions of greenhouse gases especially carbon dioxide. But during the 1970s, the new regulations favored nuclear power plants because coal-fired plants had to increase costs to pay for emission control technologies.

Examining whether the power rating size of a nuclear plant made a significant difference, the RAND study found that even with fossil-fuel plants in the late 1950s and 1960s there was no experience in building a power plant bigger than 750 MWe. Despite this lack of experience, "the constructors, designers, and buyers set out to build plants ranging from 400 to 850 MWe, and 1000 MWe plants were designed and ordered two years before any installations larger than Dresden (200 MWe) had become operational. In the rush to obtain returns to scale, the industry ignored (or perhaps never noticed) the importance of sequential learning exhibited by the progress of early LWR development. Larger plants were more difficult to build, had (contrary to expectation) lower reliability, and generated more costly (or not much cheaper) electricity than the less ambitious plants of the period."[12] This finding is relevant to today's shift toward considering *small, modular reactors* (SMRs) as a means to reduce financial risk and to build modularly designed plants that can potentially achieve economies of scale unlike the experience of and trend toward much larger nuclear power plants. This report discusses SMRs in more depth later.

In summing up the findings from the period 1946 to 1976, the RAND researchers outlined the successful elements of the LWRs' research, development, and deployment:

- From 1948-1953, there was early evaluation of the practical applicability of the LWR concepts.
- Also during that period, the Navy's reactors program and other smaller scale tests resulted in greater understanding of critical components and processes for PWRs.
- Soon after 1953, there was a national commitment to and follow-through toward a "prototype" commercial program as exemplified by the Shippingport reactor.
- This led to larger scale testing of the central elements of the PWR in a semi-operational setting that had commercial applications, for example, the Yankee Nuclear Power Station.
- Notably, sequential development and demonstration, with some overlap, permitted the results of one experiment to be evaluated and applied to the next in the series.
- One of the major principles was conservatism in design and engineering concepts during test and demonstration.
- Government subsidies played a substantial role at the beginning and intermediate phases of development and demonstration and gradually decreased as the scale of demonstration and construction grew larger.

---

[12] Ibid, p. 84.

- Finally, government decreased, and eventually stopped, its direct involvement in paying for plant construction as dependence on manufacturers for technical advances increased.[13]

The RAND study also identified several caveats and problems:

- The AEC was insensitive "to the complex, non-political, institutional elements of the demonstration process" such as the "inappropriate coupling of high-risk demonstration plants with financially constrained small utilities."

- The government reduced "R&D support, particularly for the safety elements of the light water reactor."

- The AEC discontinued "the demonstration program while some promising (design and fuel) cycles still were incompletely developed" such as the HTGR.

- As mentioned earlier, vendors and utilities had "unrealistic expectations of cost competitiveness before other than 'small' non-representative plants had been demonstrated."

- The AEC was reluctant "to accept responsibility for any effects of nuclear plant construction other than those involving nuclear safety (before 1971)."

- Government showed "indifference to the increasing public concern for safety … and environmental effects."

- Government and industry had "excessive confidence in the predictability of the future and prospects for LWRs." They were predicting the demand by the year 2000 for more than ten times the number of LWRs than were eventually constructed and operated. [U.S. electricity demand and growth in the 1980s and beyond was far less than the near exponential growth that was forecasted in the 1960s and 1970s.]

- Finally, the AEC emphasized "reactor development without adequately addressing other elements of the nuclear cycle (enrichment, reprocessing, and waste management)."[14]

Based on these adverse experiences, or at the very least, cautionary tales, the RAND researchers assessed that there would be "some unexpected consequences for the future of other nuclear (and non-nuclear) options:

- Neither utilities nor manufacturers are likely to make major commitments to potentially high cost systems or concepts that have not been demonstrated at nearly full scale.

---

[13] Ibid, pp. 84-85.

[14] Ibid, pp. 85-86.

- Government subsidies of promising new approaches probably will have to be continued farther into the test, demonstration, and proof of commercial feasibility cycle than was the case for LWRs."[15]

It is also worth underscoring the general recommendations of the RAND report because of the relevancy for future advanced nuclear and non-nuclear energy systems:

- "Cost estimating accuracy is an essential aspect of successful commercialization; the development of appropriate costing methodologies should be emphasized in all future planning.

- Analyses of future energy requirements should include consideration of alternative futures, and programs should provide specifically for adjusting investments and goals to adapt to sudden or major changes in demand, price, or technology.

- Institutionally generated pressures for continued support of some special technologies should be discounted in evaluating the need for and feasibility of various approaches; functional rather than institutional budgeting may be most appropriate for technologies approaching the commercialization phase.

- The development of a complex technological system requires *balanced* effort in all of its principal elements."[16]

Concerns about Technological Lock-In

The question remains: Has the nuclear industry experienced technological lock-in in which one technology predominates yet is not the optimum solution? There have been many examples in history of this paradigm.[17] For instance, some would argue that Microsoft's dominance with Windows operating systems for personal computers and its suite of Word software have provided decent (but not the best) solutions. However, the "best" or seemingly optimal solution might be considered too risky in terms of financial cost, technological complexity, or other features that could impede widespread consumer adoption of the technology. The real test for non-LWR technologies will be whether they can make in-roads into the commercial marketplace given the nearly 60 years of commercial experience with LWRs.

Another likely barrier to more advanced nuclear energy systems is the potential technological lock-in of uranium dioxide fuels, especially those in a once-through fuel cycle or mixed oxide fuel in once-recycle fuel cycle. That is, a fully-closed fuel cycle has not been implemented commercially in the world. (While France and Russia, for example, might seem to have closed the fuel cycle, in reality they do a once-through recycling of plutonium from irradiated fuel. The irradiated fuel from that recycling has been stored pending potential further

---

[15] Ibid, p. 86.
[16] Ibid, p. 87.
[17] Richard Perkins, "Technological 'lock-in'," International Society for Ecological Economics, Internet Encyclopaedia of Ecological Economics, February 2003.

deployment of reactors that can consume the remaining fissionable materials and thus fully close the fuel cycle.) Higher costs have held back such development as well as concerns about proliferation arising from use of breeder reactors although fast neutron reactors in a "burner" mode might help address these concerns. Moreover, the relative abundance of natural uranium given the present and foreseeable demand for nuclear power has also impeded a closed fuel cycle from being developed. Nonetheless, with certain countries such as France and Korea wanting to develop such fuel cycles for waste management reasons, it is worth pondering whether the existing fuel system could further impede progress because of technological and political inertia. Of course, before implementing, closed fuel cycles must meet nonproliferation standards and should be cost-competitive. But the cost competiveness evaluation would need to factor in a holistic systems approach, namely the potential benefits of external costs from better waste management and countries' evaluations of energy security.

The thorium-fuel system appears also to have fallen victim to technological lock-in. Thorium is not fissile alone but instead is fertile and can be transmuted into fissile uranium-233 after two radioactive decays. Thorium is estimated to be three to four times more abundant than natural uranium, and thus could in principle provide several hundred years of energy supplies. In addition, thorium fuel cycles appear to offer enhanced proliferation resistance because of the production of uranium-232, which is relatively high in radioactivity and would complicate the use of uranium-233 in nuclear weapons. However, the thorium fuel cycle is not "proliferation proof" because it is possible to separate out nearly pure uranium-233 and even the presence of uranium-232 might not stop determined use of uranium-233 in an improvised nuclear explosive device.[18] But the large amounts of thorium required and the extra expense would likely make this method prohibitive or at least not nearly as desirable as more traditional methods of producing weapons-grade plutonium. While there are groups advocating for the use of thorium as nuclear fuel, little has been done to reach commercialization (although this report later discusses the Generation IV International Forum's and others' work on reactor systems that could use thorium). It is telling that Thorium Power, a company founded about 20 years ago to commercialize thorium fuels has, in recent years, rebranded itself as Lightbridge Corporation and has been earning its revenue by providing advisory and other services for the uranium fuel market and light water reactor technologies as well as making progress in developing advanced metallic uranium-based fuels.[19] It is worth keeping in mind the principles of technological lock-in and inertia when considering the barriers that non-LWR and non-uranium fuels would have to overcome.

---

[18] Stephen F. Ashley, Geoffrey T. Parks, William J. Nuttall, Colin Boxall, and Robin W. Grimes, "Nuclear Energy: Thorium has risks," *Nature*, vol. 492, December 6, 2012, pp. 31-33.

[19] See press releases of Lightbridge Company at http://ir.ltbridge.com/releases.cfm, accessed on May 31, 2015.

Lessons Learned from the Accidents at Three Mile Island and Chernobyl: The Need for Passive and Inherent Safety Systems

Before 2011, there had been only two major nuclear power accidents in the world. In 1979, one of the reactors at the Three Mile Island (TMI) Nuclear Power Plant in Pennsylvania experienced a partial fuel meltdown. Fortunately, the containment structure remained intact and thus the public was not exposed to significant radioactivity from the accident (although the governor of Pennsylvania did order pregnant women and young children to evacuate as a precaution). The TMI reactor was a pressurized water reactor.

A much worse accident happened seven years later at the Chernobyl Nuclear Power Station in Ukraine when the operators placed one of the reactors into an unsafe operating mode, ironically during a test of safety systems. The reactor was an RBMK, or graphite-moderated, water-cooled reactor, with design flaws that became apparent when the operators took actions to place the reactor in an unusual condition that then led to the accident. One major flaw was that when the control rods were inserted, the reactivity initially increased because the ends of the rods were made of graphite, which moderated the neutrons and thus spiked reactivity. The accident resulted in a steam and hydrogen gas explosion that blew the top off the roof of the reactor building. This power plant did not use a strong containment system (unlike TMI). Massive amounts of radioactive contamination spread widely across Europe. This contamination triggered alarm in many European countries and contributed to numerous people in several countries expressing opposition to nuclear power. Thus, by 1990, the outlook for nuclear power in much of Europe looked unpromising. Something had to change to make nuclear power acceptable again.

According to a major study in 1991 by Charles Forsberg and William Reich at Oak Ridge National Laboratory, "The key characteristic of the TMI and Chernobyl accidents was that the operators shut down functional safety systems for what seemed to be good reasons at the time. If those safety systems had remained operational, the accidents would not have occurred. These were accidents of commission—deliberate actions by operators—not equipment failures or failure to follow instructions. The solution proposed to eliminate these and other safety issues is the use of passive and inherent safety. It is a radical change in technology. Whether it will be a technical, economical, and institutional solution to solve the problems associated with nuclear power is unknown."[20]

This was one of the first major reports to emphasize a shift in passive safety systems that could even be considered inherently safe (although one could not rule out operators still trying to intervene incorrectly). The analysis in Forsberg and Reich's report was illuminating. They defined the acronym PRIME to signal their proposed "radical" change. PRIME stood for "Passive safety, Resilient safety, Inherent safety, Malevolence resistance, and Extended time for external aid after an accident."

---

[20] Charles W. Forsberg and William J. Reich, "Worldwide Advanced Nuclear Power Reactors with Passive and Inherent Safety: What, Why, How, and Who," Oak Ridge National Laboratory, ORNL/TM-11907, Prepared for the U.S. Department of Energy, September 1991.

Forsberg and Reich underscored passive safety throughout their report because of the past history of nuclear power accidents. They also examined economics primarily through the lens of safety. For instance, their report cites studies that show that "30 to 60% of the cost of nuclear power is related to health, safety, and environment. This implies that if major improvements in economics are to be obtained, new approaches to safety are required. The cost of active safety systems is a major factor in the cost of nuclear power."[21] They also highlighted the cost of money in making investments and how investors became wary in spending their money on nuclear power given the perception of safety concerns following the accidents. It is also interesting to note that they drew attention to the "greenhouse effect" and how this might help make the case for further expansion of nuclear power. But they also cautioned that it is challenging for nuclear power "to be used on a large scale in underdeveloped countries" with "increased concerns about the low skill levels, political instabilities, and limited resources applied to safety. These factors may increase accident probabilities if passive and inherent safety technologies are not used."[22] All the issues they raised in 1991 are still relevant today and have influenced the designs of many of the proposed advanced nuclear energy systems considered in the following section.

---

[21] Ibid, p. 6.

[22] Ibid, p. 7.

A New Millennium and a New Era for Nuclear Power: The Creation of the Generation IV International Forum and Its Roadmaps

During the 1990s, nuclear power plant construction stagnated around the world. While there was continued significant construction efforts in a few countries, notably Korea, most of the major nuclear power producing countries had all but stopped the building of reactors. During that time in particular, the United States had not ordered a new plant since the TMI accident and had cancelled many orders for plants. France and Japan experienced a major upsurge in construction during the 1980s which then declined in the 1990s having mostly reached their nuclear energy generation goals. As mentioned in the previous section, this major downturn was in most of Europe in response to the Chernobyl accident. Voters in several countries passed referenda that resulted in government policies to phase out, or at least not expand use of, nuclear power.

Even with a plateau in nuclear power plant construction, several countries still moved forward with research and development of advanced reactor designs. Korea, for example, explored a technology known as DUPIC that would reuse uranium and could burn up transuranic elements in pressurized heavy water reactors in order to better manage and reduce the volume of nuclear waste needing to be stored.[23] The Korea Atomic Energy Research Institute (KAERI) also developed small modular reactor designs such as SMART, which has now reached the point where it can take the next steps for commercial development. In addition, KAERI examined other proliferation-resistant methods for advanced nuclear energy systems, such as using pyroprocessing to make mixtures of transuranic and fission product material for eventual consumption in fast neutron reactors (including sodium-cooled fast systems). The United States has continued its R&D efforts at various national laboratories such as Argonne, Idaho, Oak Ridge, and Los Alamos. The Argonne National Laboratory, in particular, devoted significant work on the integral fast reactor combined with pyroprocessing. The funding, however, was suddenly cut during the Clinton administration in 1994. U.S. nuclear R&D largely shifted during that period toward light water reactor systems, which were considered well proven and well entrenched. Additional R&D took place in Japan, Russia, and the European Union. While a comprehensive list of these activities is beyond the scope of this report, this report does recognize that these R&D activities formed the basis for a more formalized and multi-nationally cooperative approach to advanced nuclear energy systems.

In January 2000, under the auspices of the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD), headquartered in Paris, France, several countries undergoing the aforementioned R&D activities and others wanting to further these activities came together to form the Generation IV International Forum (GIF). GIF, in addition, received substantial resource and staffing support from the U.S. Department of Energy's Nuclear Energy Research Advisory Committee (NERAC). U.S.

---

[23] For example, see: A. C. Morreale, W. J. Garland, and D. R. Novog, "The Reactor Physics Characteristics of a Transuranic Mixed Oxide Fuel in a Heavy Water Moderated Reactor," *Nuclear Engineering and Design*, Vol. 241, Issue 9, September 2011, pp. 3768-3776, shows simulations that indicate substantial consumption of transuranic material when formed into a mixed oxide fuel in a PHWR computer model.

lead representative William Magwood IV became the first chairman of GIF. (He is now the head of the NEA.) The GIF Charter, officially established in July 2001, was initially comprised of nine founding members and has subsequently expanded to 13 members: Argentina, Brazil, Canada, China, Euratom, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland, the United Kingdom, and the United States. In 2002, GIF published a technology roadmap with four main goals to achieve the fourth generation of nuclear power systems:

I. "Sustainability
   - Generate energy sustainably and promote long-term availability of nuclear fuel.
   - Minimize nuclear waste and reduce the long-term stewardship burden.

II. Safety and reliability
   - Excel in safety and reliability.
   - Have a very low likelihood and degree of reactor core damage.
   - Eliminate the need for offsite emergency response.

III. Economic competitiveness
   - Have a life cycle cost advantage over other energy sources.
   - Have a level of financial risk comparable to other energy projects.

IV. Proliferation resistance and physical protection
   - Be a very unattractive route for diversion or theft of weapon-usable materials, and provide increased physical protection against acts of terrorism."[24]

This roadmap also described the necessary R&D to accomplish full deployment of these systems after 2030. The systems included the nuclear reactors, the energy conversion systems, and the fuel cycles. Interested readers are advised to visit the GIF website for the full report.[25] Here, this report provides an overview of the six nuclear energy systems selected for inclusion in GIF.

The selection process winnowed from almost 100 different design concepts to only six. GIF, however, does not want to suggest that these six would be the only viable future nuclear energy systems. Moreover, these six designs can involve various modes of operation and different fuel systems and thus can, in effect, be considered to be more than just six designs. Notwithstanding, these six were deemed to be far enough along, based on previous R&D and some operating experience, for several types of these systems. These six designs also represent a mix of evolutionary systems following the current light water reactor systems to many revolutionary energy systems, departing significantly from almost all presently operating commercial reactors (except for a few sodium-cooled fast reactors in use in Russia

---

[24] GIF Roadmap report, January 2014, pp. 14-15.

[25] The full report, A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, 2002, is available at www.gen-4.org.

and India and in development in Korea, Japan, and France). For a detailed description of the reactor systems as well as the latest GIF roadmap for next important steps for each system, readers can access the January 2014 GIF report;[26] here, the main features and urgent R&D needs of each system are noted as a guide to the findings of this report. To prove commercial viability, each nuclear energy system will have to undergo extensive work in three successive phases:

I. "The viability phase, when basic concepts are tested under relevant conditions and all potential technical show-stoppers are identified and resolved;

II. The performance phase, when engineering-scale processes, phenomena, and materials capabilities are verified and optimized under prototypical conditions; and

III. The demonstration phase, when detailed design is completed and licensing, construction, and operation of the system are carried out with the aim of bringing it to the commercial deployment stage."[27]

Before describing the specific designs, it is worth underscoring some general features that are common to all (or most of) these designs. First, all of these designs offer significantly higher energy efficiencies than the presently operating thermal reactors, including all light water reactors and heavy water reactors. Typically, it is estimated that the six GIF designs could provide efficiencies from 40 to almost 50 percent in comparison to the usual 33 to 34 percent for thermal reactors while some power up-ratings have boosted light water reactors up to 36 percent. Higher energy efficiency means more electrical energy and other useful energy such as hydrogen fuel production per unit of heat energy in the reactor core and thus less wasted heat energy that would be released into the environment. Higher efficiencies would help in saving fuel costs and could help make advanced nuclear energy systems more competitive with fossil fuel energy systems. (For example, combined cycle natural gas power plants can achieve 50 to 60 percent efficiencies.) The GIF designs achieve higher efficiencies primarily via higher operational temperatures. Several of these designs can also use highly efficient Brayton power cycles in comparison to the steam Rankine cycle of today's thermal reactors.[28] The GIF designs, in addition, have higher reactor power densities. Moreover, several of the designs envision on-site integrated, or close-proximity, means for processing and recycling spent fuel, resulting in better waste management.

Gas-Cooled Fast Reactor (GFR)

The GFR uses helium for cooling of, and heat transfer from, the reactor core, which is a fast neutron reactor. It is envisioned that the GFR will have a closed fuel cycle with multiple recycling functions to consume long-lived actinides for waste minimization. One advantage

---

[26] See: Generation IV International Forum, Technology Roadmap Update for Generation IV Nuclear Energy Systems, Issued by the OECD Nuclear Energy Agency, January 2004.
[27] GIF Roadmap report, p. 8.
[28] See, for example, the following website for an accessible technical explanation of the Brayton cycle: http://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node27.html, accessed on May 31, 2015.

of the GFR is that helium is chemically inert and would not have corrosion or radiotoxicity problems as compared to other high temperature systems. Notably, GFRs could provide very high thermal efficiencies of about 48 percent. General Atomics has claimed that its EM2 GFR design might even reach 53 percent thermal efficiency.[29]

Granted, with the use of GFR, there are significant challenges associated with such high temperatures, as well as other demanding operational conditions. Because of the low thermal inertia, the core could experience rapid heating in the event of loss of forced cooling, which could potentially result in a meltdown. This loss of forced cooling could happen through depressurization. Moreover, because the power density is high, conduction cool-down will not function as it would for other types of high temperature gas-cooled reactors (HTGRs). In addition, the helium density is too low to provide sufficient natural convection for core cooling. Furthermore, research is needed to address the effects of fast neutron bombardment on the pressure vessel. In contrast, other traditional HTGR systems use graphite moderation that will slow down the neutrons and thus mitigate the neutron bombardment on the pressure vessels.

The GIF Roadmap emphasizes that there remains a need "for a small experimental reactor to be available within the next 10-20 years. The ALLEGRO experimental reactor project currently being undertaken by a consortium of four countries (the Czech Republic, Hungary, Poland, and the Slovak Republic) fulfils this requirement. ALLEGRO will be the first fast spectrum gas-cooled reactor to be constructed and will be the test bed to develop and qualify the high-temperature, high-power density fuel that is required for a commercial scale high-temperature GFR."[30] This reactor will be around one-tenth of the power rating of a full-scale GFR.

Another critical need is creation of an acceptable fuel system. In particular, a cladding material for the fuel that meets core specifications, including leak tightness, ductility, compatibility with helium that could have impurities, and the intense radiation conditions, is needed. The GIF Roadmap specifies criteria of:

- "Clad temperature of 1,000° C, during normal operation;
- No fission product release for a clad temperature of 1,600° C during a few hours; and
- Maintaining the core-cooling capability up to a clad temperature of 2,000° C."[31]

The fuel development will require international collaboration, as no specific country has the requisite expertise for this system. GIF recognizes that this system will need considerable R&D effort to move it to a commercial consideration stage. First, over the next 10-20 years, the design of the small experimental reactor will have to be finalized, and then the decision will have to be made about the licensing process for the experimental reactor. Perhaps by

---

[29] See http://www.ga.com/websites/ga/docs/em2/pdf/FactSheet_QuickFactsEM2.pdf, accessed on May 31, 2015.
[30] GIF Roadmap, 2014, pp. 20-21.
[31] Ibid, p. 21.

2025, this reactor will reach the performance demonstration phase. The GIF Roadmap does not project out beyond 20 years and thus does not anticipate a commercial prototype within that time period.

In a recent independent study of the prospects for advanced nuclear energy systems, the Breakthrough Institute, a non-governmental organization based in Oakland, California that strongly favors nuclear energy, assessed that GFRs may face too many significant hurdles to reach commercialization. They drew attention to the lack of existing materials that can withstand high irradiation fields that would be present in GFRs' cores; the fact that no gas-cooled fast reactor has even been built for testing purposes; and "the reliance on engineered safety systems rather than inherent safety features undermines its potential as a meltdown-proof design."[32]

Lead-Cooled Fast Reactor (LFR)

The LFR uses lead (Pb) or lead-bismuth (Pb-Bi) alloy coolant at atmospheric pressure and high temperature due to the very high boiling point of the coolant. Because of the neutron scattering properties of lead, the chain reaction makes use of fast neutrons. The expected efficiency of the LFR is above 42 percent and there are a number of attractive safety properties, including:

- The chemical inertness of the coolants; in particular, lead does not react exothermically with water or air unlike liquid sodium (as discussed later);
- The high boiling point of lead reduces the risk of voids being created in the core (that is, the core will tend to be covered with coolant);
- The high density of lead helps with fuel dispersion instead of compaction in the event of core destruction, minimizing the risk of a criticality accident;
- The thermal properties of lead provide thermal inertia;
- Lead shields gamma rays and also retains some highly radioactive fission products in the event of an accident;
- Lead has very low neutron moderation that allows for increased spacing between fuel pins and thus reducing the risk of coolant flow blockage; and
- The simplified coolant flow path and low core pressure drop provide natural convection cooling for shutdown heat removal.

However, LFRs still have challenges that need to be addressed. First, to prevent lead's erosive and corrosive effects on structural steel at high temperatures and flow rates, there is

---

[32] Ted Nordhaus, Jessica Lovering, and Michael Shellenberger, "How to Make Nuclear Cheap: Safety, Readiness, Modularity, and Efficiency," The Breakthrough Institute, June 2014, p. 49.

the need for chemical control by introducing oxygen into the coolant, creating an oxidizing layer in the structural materials. In the event of an earthquake, the high structural stress from heavy lead might damage the reactor. Due to lead's opacity, monitoring and inspecting the core's components is difficult. Because of lead's high melting point, the primary coolant has to be maintained above 327ºC to prevent solidification of the coolant. Moreover, due to the heavy metal toxicity of lead, special procedures would have to be developed and implemented to dispose of it safely.

The only significant operating experience of Pb-Bi reactors has been their use in about a half dozen Russian submarines, two of which experienced major reactor problems. Also, it is not easy to extrapolate the successful submarines' reactors' experience to the LFR notional design because they were operated at significantly lower temperatures and used an epithermal (not fast) neutron spectrum. A safety issue of these reactors was the accumulation of polonium-210, a strong alpha-emitter; the Russian Federation developed techniques to trap and remove the polonium.

Several contrasting designs and power rating sizes are being studied in a number of countries, including China, Korea, Japan, Russia, the United States, and member countries of Euratom. Interested readers wanting to know more about the various activities are invited to consult the Gen IV's 2014 Roadmap and website. The country furthest along to a prototype demonstration after 2020 is most likely Russia with its BREST-OD-300 and SVBR-100 reactors based on the Russian navy's previous experience.

Most likely, if LFRs were to reach commercialization, they would be smaller in size to keep the total weight and volume of lead low. For instance, Gen4 Energy (formerly known as Hyperion Power) is developing the Gen4Module, a small 25 MW modular LFR with a 10-year lifetime.[33] These so-called "nuclear batteries" appear to offer the most promising pathway forward for LFRs (assuming that significant technical challenges, as mentioned above, can be overcome).

Molten Salt Reactor (MSR)

The MSR is typically classified into two types of designs. In the first type, fissile material is dissolved in a molten fluoride salt. The second type uses the molten salt as a coolant for a core fueled with coated fuel particles. The coating provides protection by blocking radioactive fission products from entering the coolant. In contrast, the first type would use a method to capture the fission products that are circulating in the molten salt. But with either method, ensuring an environment free of radioactive contamination is a primary objective.

A relatively old idea, the MSR has received substantial attention in recent years, from staunch, long-standing proponents of proliferation-resistance to bright, younger engineers at MIT and Silicon Valley venture capitalists. Those who do not know the history of the MSR might be surprised to learn that it derived from the 1950s investigation of the Aircraft Reactor Experiment, which attempted to design and build a nuclear reactor safe enough to power airplanes. While this experiment did not result in nuclear-powered aircraft (probably thankfully so), it did lead to the Molten Salt Reactor Experiment at Oak Ridge National

---

[33] For details, see http://www.gen4energy.com, accessed on May 31, 2015.

Laboratory. The legendary nuclear energy leader Dr. Alvin Weinberg worked on this experiment and was a proponent of this technology. But by the early 1970s, the United States government had pulled funding for the experiment or for further R&D to continue investigating MSRs.

The revival of recent interest has much to do with the safety features of MSRs. For example, they would have large negative temperature and void reactivity coefficients, meaning that fast temperature increases or the creation of vacuums or less dense volumes, or "voids," would decrease reactivity and thus drive the reactor into a safer status. In the first design type, where fissile material dissolved in the salt, if electrical power is lost, a frozen plug at the bottom of the primary piping will melt and result in the molten material flowing and sinking to a safe container. Moreover, since these reactors operate at or near atmospheric pressure, there are not potential safety problems due to loss of pressurization as in PWRs or even GFRs.

Another reason for excitement about MSRs is proliferation-resistance. In a mode under which MSRs use the thorium-232/uranium-233 fuel cycle, the reactors are believed to offer significant proliferation-resistance. Although U-233 is fissile and would be useful in first-generation gun-type nuclear explosives, the thorium-uranium fuel cycle would produce uranium-232, which, in even relatively small proportional amounts, would create a radiation hazard for any workers attempting to form the uranium mixture into nuclear bombs.[34] Because uranium-232 and uranium-233 have nearly identical chemical properties, it would not be possible to use chemical processing techniques to separate them. However, there is a possibility that protactinium, the intermediate element in the chain of production from thorium-232 to uranium-233, could be separated early enough in the production process to reduce the creation of uranium-232. With a half-life of about 27 days, protactinium-233 decays to uranium-233. But to even make one kilogram of uranium-233, it would require about 1.5 metric tons of thorium-232.[35] To get enough uranium-233 for even one bomb would require eight times this amount of thorium. Thus, although this fuel cycle is not proliferation-proof, it appears to offer significant proliferation-resistance.

The stumbling block in adoption of the thorium fuel cycle appears to be that the once-through uranium fuel cycle is very entrenched, as mentioned earlier in this report. However, countries with abundant supplies of thorium (such as India) have expressed interest in developing prototypes. Thorium is estimated to be three to four times more abundant than uranium. The liquid fluoride thorium reactor (LFTR) has received significant attention as a promising technology.[36]

---

[34] For an independent assessment of this fuel cycle, see Jungmin Kang and Frank N. von Hippel, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel," *Science & Global Security*, Vol. 9, 2001, pp. 1-32.

[35] Stephen F. Ashley, Geoffrey T. Parks, William J. Nuttall, Colin Boxall, and Robin W. Grimes, "Nuclear Energy: Thorium has risks," *Nature*, vol. 492, December 6, 2012, pp. 31-33.

[36] Robert Hargraves and Ralph Moir, "Liquid Fuel Nuclear Reactors," *Physics and Society*, January 2011, http://www.aps.org/units/fps/newsletters/201101/hargraves.cfm.

Moreover, the second design type, often called fluoride salt-cooled high-temperature reactor (FHR), has features that might allow large-scale power generation with full-scale passive safety characteristics. In addition, FHRs offer high-efficiency electricity generation coupled with process heat production for industrial purposes. A newer design from researchers at MIT, the University of California, Berkeley, and the University of Wisconsin combines an FHR with a natural gas power plant to give base load and peaking electrical power distribution. The MIT-Berkeley-Wisconsin team has done an economic cost-benefit analysis that indicates that this hybrid mode of electricity generation might make this type of FHR cost competitive with fossil-fuel power plants.[37]

Another example of an FHR that has had some significant R&D is the pebble-bed advanced high-temperature reactor (PB-AHTR), which uses TRISO ceramic fuel particles. Research on TRISO fuel dates back to 1959 in the United Kingdom. This fuel type was later tested in two German gas-cooled reactors. More recently, China and Japan have investigated TRISO fuels. PB-AHTR designers are planning to apply modular construction principles used in Korea and China.

Furthermore, MSRs could offer significant benefits in nuclear waste management. Because of their fuel versatility, these reactors might be able to consume many fissionable materials, such as those greater in mass than uranium. This could help alleviate the long term burden on nuclear waste repositories, such that a batch of radioactive material would only have to be stored for a few hundred years until it reaches low levels of radioactivity in contrast to tens of thousands of years for the once-through uranium fuel cycle. For example, Transatomic Power, a recent startup company founded by two younger MIT-educated nuclear engineers is investigating this design under the title of Waste-Annihilating Molten Salt Reactor (WAMSR).[38] But much more research is needed to develop this transuranic consuming reactor concept. There might need to be multiple recycles in order to have burn up that results in very low levels of transuranic materials.

What are the additional challenges for MSRs? For FHRs, they will need further research on fiber ceramic composites, fuel elements and assemblies, tritium release prevention technologies, and corrosion protection technologies.[39] For the other major design concept, several R&D issues need to be addressed, including the physical-chemical behavior of fuel salts and the behavior of radioactive fission products in the salts, the compatibility of salts with structural materials for fuel and coolant circuits, on-site fuel processing methods, as well as instrumentation and control of liquid salt.[40]

---

[37] Charles Forsberg, Per F. Peterson, Lin-Wen Hu, and Kumar Sridharan, “Baseload nuclear with variable electricity to the grid,” *Nuclear News*, March 2015, pp. 77-81.

[38] Bryan Walsh, “Amid Economic and Safety Concerns, Nuclear Advocates Pin Their Hopes on New Designs,” Time.com, August 5, 2013; Josh Freed, “Back to the Future: Advanced Nuclear Energy and the Battle Against Climate Change,” Brookings Magazine, December 2014.

[39] See: David E. Holcomb et al., “Fluoride Salt-Cooled High-Temperature Reactor Technology Development and Demonstration Roadmap,” Oak Ridge National Laboratory technical report, September 2013.

[40] GIF Roadmap, 2014, pp. 31-32.

While significant research challenges remain, the safety features and other potential benefits make MSRs attractive. Also, considering the R&D that has been done particularly on the PB-AHTR concept, some analysts predict a move toward commercialization by the mid-2020s.[41]

Sodium-Cooled Fast Reactor (SFR)

Similar to some other *Generation IV* design concepts, the SFR is not a "new" technology as several nations have had R&D and prototype commercial-scale SFRs for decades. As mentioned in the beginning of this report, nuclear engineering pioneers in the 1940s were exploring this concept because of the perceived need for breeder reactors. The SFR uses liquid sodium as coolant in a fast-neutron reaction. Liquid sodium allows for a low-pressure coolant system with a high-power density core. Due to its physical and chemical properties, liquid sodium also has high thermal inertia and a large margin to coolant boiling, both of which are important safety features. But the biggest safety concern remains that sodium reacts chemically with air and water and thus needs a sealed coolant system.

The GIF 2014 Roadmap highlights three options for SFRs: pool, loop, and modular. Thus, the GIF research plan has three sizes of SFR that are being studied:

I. "A large size (600 to 1500 MWe) loop-type reactor with mixed uranium-plutonium oxide fuel and potentially MA [minor actinide]-bearing fuels, supported by a fuel cycle with advanced aqueous processing at a central location serving a number of reactors;

II. An intermediate-to-large size (300 to 1500 MWe) pool-type reactor with oxide or metal fuel; and

III. A small size (50 to 150 MWe) modular type reactor with metal-alloy fuel (uranium-plutonium-MA-zirconium), supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor."[42]

According to the GIF Roadmap, the SFR "is an attractive energy source for nations that desire to make the best use of limited fuel resources and manage nuclear waste by closing the fuel cycle. Its fast neutron spectrum enables full actinide recycling and greatly extends uranium resources compared to thermal reactors. The SFR technology is more mature than other fast reactor technologies and thus is deployable in the very near-term for actinide management. With innovations to reduce capital cost, the SFR also aims to be economically competitive in future electricity markets."[43]

Researchers outside of GIF who are concerned about proliferation have produced a lengthy report that critiques SFRs. That group points to a long history of sodium leaks and some sodium fires at experimental reactors in a number of countries. They also view SFRs as too expensive as compared to LWRs given the added features that would have to be put in place

---

[41] See, for example, the Breakthrough Institute 2014 report, p. 37.
[42] GIF Roadmap 2014, p. 34.
[43] Ibid, p. 35.

to minimize the likelihood of sodium leaks. Moreover, they express skepticism that uranium shortages will increase uranium prices such that SFRs appear attractive from a breeding and plutonium recycling perspective.[44] Nonetheless, countries with concerns about energy security such as Korea, Japan, and France still have interest in SFRs, but of these countries, Korea is most likely to move forward due to its needs for reducing the volume of high level waste and for removing transuranics from this waste that would require tens of thousands of years of storage. Japan is struggling with the future of its LWRs, and (even though Monju's SFR is an older design from before 1985) the 1995 sodium fire at Monju has stalled further development of this technology in that country. About five years ago, France shut down its only operating SFR. However, China, India, and Russia are notably pursuing SFR-type technologies with Russia having the most operating experience of those countries.

Further research is needed to ensure that the sodium remains well sealed while not having the additional sealant equipment increase the cost; this would allow the plant to become economically competitive. Also, "void swelling," or the tendency of metallic fuel elements to swell under irradiation, and build-up of fission product gases has been a problem with past SFRs. Methods to vent these gases can mitigate void swelling. In addition, R&D is required to ensure that materials can withstand neutron embrittlement and metallic creep under prolonged radiation exposure, key for reactors designed to last up to 60 years. Further work is also needed in developing on-site reprocessing systems. While Argonne National Laboratory did investigate this method with the integral fast reactor (IFR) system under development in the 1980s and into the 1990s, the program's funding was cut in the mid-1990s. Joint research between Korea and the United States in pyroprocessing might result in demonstrating the viability of this type of method. The full system, however, would have to be demonstrated in a prototype. Korea is aiming to build a prototype by 2028 and then move toward deployment of a full-scale commercial system in the decade after that year.[45] Japan continues to express interest in SFRs, but as mentioned, the long shutdown of the Monju reactor and the continued shutdown of Japan's thermal reactors raise doubts about Japan's capacity to renew its SFR program in the coming years.

Supercritical-Water-Cooled Reactor (SCWR)

By increasing temperatures and pressures to the part of the water phase diagram in which water becomes supercritical, the designers of the SCWR aim to create a highly efficient power plant. When water is supercritical, steam and liquid have the same density, so the SCWR does not require extensive equipment to separate and dry steam, and the supercritical water goes directly from the reactor to the turbine. This design simplicity saves on expensive steam generators, steam dryers, recirculation pumps, and secondary cooling system. By not requiring all of these pieces of equipment, the plant can be made significantly smaller than a typical PWR (but with an equal power rating). The efficiency is estimated to be 45 percent.

---

[44] Thomas B. Cochran et el., "Fast Breeder Reactor Programs: History and Status," A Research Report of the International Panel on Fissile Materials, February 2010.

[45] Yeong-il Kim, "Status of SFR Development in Korea," KAERI representative's presentation to FR13, Paris, France, March 5, 2013, https://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-03-04-03-07-CF-NPTD/T1.1/T1.1.kim.pdf, accessed on June 11, 2015.

However, like the PWR, the SCWR has features that have raised safety concerns. The water coolant can be corrosive; the pressurized system requires engineered safety systems; and backup power is needed to keep the water in a supercritical state. In particular, the pressure vessel would have about 1.5 times the pressure of a typical PWR's pressure vessel. This fact makes implementation of passive safety systems increasingly challenging. Also, the fast neutron model of an SCWR has a positive void coefficient that may result, if steam bubbles or a vacuum forms, in uncontrolled heating from reactivity surges. Advanced, very rigorous and corrosion-resistant materials will have to be developed for the SCWR to be viable.

As to the commercial pathway, one advantage is that the U.S. Nuclear Regulatory Commission (NRC) is very familiar with pressurized water reactor systems, and this could fare well for the SCWR. But the NRC would need to know whether the issues regarding materials have been resolved. The Breakthrough Institute assessed that this is "one of the least promising Gen IV designs due to its higher core temperatures, its greater neutron flux, and its use of novel materials."[46] Moreover, the R&D challenges are estimated to take many years for testing and optimization to qualify for meeting engineering standards such as American Society of Mechanical Engineers (ASME) codes. The GIF Roadmap mentions few countries that are actively pursuing research on SCWRs and that such work mostly consists of conceptual modeling of designs. That Roadmap emphasizes the need for extensive testing of materials within the next five years and then proceeding to tests of a small-scale fuel assembly and potentially a SCWR prototype in the ten-year time horizon.[47]

Very-High-Temperature Reactor (VHTR)

The VHTR can be considered more of an "evolutionary" rather than a "revolutionary" design, given the previous experience with earlier generation, high-temperature, gas-cooled reactors. The exciting potential of the VHTR is its operating temperatures between 750°C and 950°C and the possibility of even more than 1000°C in the future. These very high temperatures can permit highly efficient generation of electricity (47 percent for 850°C and 50 percent for 950°C operations) and production of hydrogen through thermochemical processes, which are efficient means to generate hydrogen. The hydrogen can then be used in a variety of applications such as fuel cells for powering vehicles and buildings without harmful emissions. Also, a VHTR can supply heat for industrial processes in refineries and petrochemical applications. The reactor core of a VHTR can use a prismatic-block-type fuel such as the Japanese HTTR or a pebble-bed type fuel such as the Chinese HTR-10.

These reactors have safety features that are believed to reduce significantly the likelihood of major accidents. Moreover, the strong negative temperature coefficient of reactivity and the high heat capacity of the graphite core are specific reasons for this safety assessment. In addition, tests of the TRISO fuel have indicated that this reactor concept "does not need off-site power to survive multiple failures or severe natural events such as occurred at the Fukushima Daiichi nuclear station."[48] In particular, in 2004, China performed a loss of coolant test of an HTGR in front of a panel from the International Atomic Energy Agency, and the reactor demonstrated that it dissipated heat without any human or mechanical

---

[46] The Breakthrough Institute, 2014, p. 39.
[47] GIF Roadmap, 2014, pp. 42-45.
[48] Ibid, p. 46.

intervention.[49] These reactors' low power densities make it difficult for them to overheat. The helium coolant is also non-corrosive.

This reactor type is likely to be the closest to commercialization of the advanced thermal type reactors considering the operating experience of the previous generation and the assessment that construction materials are already certified. Similarities with LWRs could pave the way for NRC certification and eventual licensing. However, the unique heat dissipation feature of a VHTR could hold up NRC's certification because the NRC's rules have focused on assessing means for preventing loss of coolant rather than heat dissipation through natural means after coolant has been lost. China has experience with prototype pebble-bed reactors and is moving toward potential construction of a commercial-scale HTGR by 2020. This might then lead to eventual construction of a VHTR after 2020. In the United States and other countries, public-private partnerships between government and chemical companies needing process heat could help jump start demonstration of a commercial-scale VHTR. Such a partnership could leverage a cost-sharing grant.[50]

GIF's Working Groups

From its start, GIF recognized that progress on these systems depended on a thorough understanding of the economics, safety, and proliferation resistance and physical protection requirements. Three working groups were formed to investigate these important issue areas. Presented below are the main points that need to be addressed by each working group.

Economic Modeling Working Group

If the advanced nuclear energy systems are not cost-competitive over other energy sources, they will not be adopted by utilities. While a carbon tax or cap-and-trade scheme would help nuclear power, this cannot be counted on to take place, especially in the United States given the highly partisan split over taxation and the size and role of the federal government. GIF has not relied on factoring in carbon fees in its economic assessments. GIF's Economic Modeling Working Group has worked to develop methodology and tools that would assess these systems on the bases that there would be:

I. A life cycle cost advantage over other energy sources (i.e. to have a lower levelized unit cost of energy over their lifetime)[51]; and

II. A level of financial risk comparable to other energy projects (i.e. to involve similar total capital investment and capital at risk).

---

[49] The Breakthrough Institute, 2014, p. 29.

[50] Ibid, p. 33.

[51] Levelized cost of electricity "represents the per-kilowatt hour cost (in real dollars) of building and operating a power plant over an assumed financial life and duty cycle," according to William Pentland, writing in Forbes.com, November 29, 2014, http://www.forbes.com/sites/williampentland/2014/11/29/levelized-cost-of-electricity-renewable-energys-ticking-time-bomb/

This working group also recognized that each country has specific economic and energy security assessments that could result in differing decisions about GIF energy systems. To assist in decision-making, the working group is iterating, as work progresses on each system, an integrated economic model to compare the various GIF technologies, "as well as to answer optimal configuration questions, such as which fuel cycle is most suitable in different parts of the world and what are the optimal deployment ratios."[52] In future years, the working group will continue to refine its G4ECONS cost estimating code with substantial input from the R&D being done on the various systems.

Risk and Safety Working Group

In the past few years, this group has focused on creating an integrated framework for assessing risk and safety issues. Specifically, it is building on its 2011 report titled "An Integrated Safety Assessment Methodology (ISAM) for Generation IV Nuclear Systems."[53] This framework would be used in three main ways:

I. "Throughout the concept development and design phases with insights derived from ISAM serving to actively drive the course of the design evolution. In this application, ISAM is used to develop a more detailed understanding of design vulnerabilities and resulting contributions to risk. Based on this detailed understanding of vulnerabilities, new safety provisions or design improvements can be identified, developed and implemented relatively early;

II. Selected elements of the methodology will be applied at various points throughout the design evolution to yield an objective understanding of risk contributors, safety margins, effectiveness of safety-related design provisions, sources and impacts of uncertainties, and other safety-related issues that are important to decision makers; and

III. ISAM can be applied in the late stages of design maturity to measure the level of safety and risk associated with a given design relative to safety objectives or licensing criteria. In this way, ISAM will allow evaluation of a particular Generation IV concept or design relative to various potentially applicable safety metrics or 'figures of merit.' This post facto application of ISAM will be useful especially for decision makers and regulators who require objective measures of safety for licensing purposes or to support certain late-stage design selection decisions."

Proliferation Resistance and Physical Protection Working Group

This working group has worked closely with the Risk and Safety Working group due to overlapping issues. The Proliferation Resistance and Physical Protection Working Group has especially coordinated its efforts with the International Atomic Energy Agency's Innovative Nuclear Reactors and Fuel Cycles (INPRO) and safeguards division. An IAEA

---

[52] GIF Roadmap 2014, p. 53.

[53] https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/gif_rsgw_2010_2_isamrev1_finalforeg17june2011.pdf, accessed on May 31, 2015.

representative sits on the GIF working group. Specific countries have applied this working group's framework to evaluation of alternative spent fuel separation technologies.

This group is emphasizing to GIF and member nations that new and innovative designs need to incorporate proliferation resistance and physical protection principles into the designs. Safeguards are expected to be more effective if they are enabled by design. Thus, a close working relationship is needed between safeguards specialists at the IAEA and member nations and the designers of Gen IV systems.

Small is Attractive: Why there is Renewed Interest in Small, Modular Reactors

In a sense, submarines' reactors are small reactors and have been in use for 60 years. But these reactors were not initially designed with economic competitiveness in mind. They were (and are) intended to meet rigorous military missions. Nonetheless, companies such as Babcock & Wilcox, which are involved with naval reactors, have ventured into the commercial sector to develop LWR-versions that can start at small power levels of 50 to 300 MWe and then be scaled up by combining multiple modular reactors to essentially form larger power blocks on the order of 600 to 1200 MWe. SMRs have generated excitement in the Department of Energy and in other countries nuclear research agencies because they appear to offer a means to scale up by starting at an apparently manageable $1 billion or so cost. Then, as a utility can afford to add on other modules over time, the power generated can go up. Still, utilities, certainly those in the United States, are risk-averse, and they would be reluctant to spend $1 billion on a new technology. Consequently, despite U.S. government support for some tens of millions of dollars for SMRs, the scale of the financial commitment will most likely need to be an order of magnitude higher, and the government could stimulate deployment by demonstrating one or more SMRs to power military bases or national laboratories.

Another reason for rising excitement in SMRs is that they appear well-suited for many countries in the developing world that have smaller electrical grids. A general rule is that an electrical grid should not have more than 10 percent of its power coming from one power plant. For example, a 1,000 MWe typical LWR would not be suitable for a grid that could only manage 8,000 MWe. This size LWR might "trip the grid" when it is brought on- or off-line. While SMRs have sometimes been described as "plug-and-play," they will still require extensive training of personnel in the developing countries that order them. Even SMRs that have lifetime reactor cores or SMRs that are buried underground will need well-trained security forces to protect them. Thus, SMRs have generated significant excitement for good reason, but their management will still need adequate attention to ensure safety and security.

While detailed explanations of the designs of SMRs are beyond the scope of this report, the following are presented as salient features of some companies' and research institutes' designs that are of recent or renewed interest. A number of the GIF designs are envisioned in smaller and modular sizes, such as the LFR, MSR, and SFR, for reasons described in previous sections.

- Babcock & Wilcox Nuclear Energy, Inc. has designed the mPower advanced light warer reactor. This design is an integral PWR or iPWR that has passive and other innovative safety features incorporated in a self-contained module with the reactor core and steam generator located in a common reactor vessel; that is the "integral" aspect of the design. The mPower design is rated at 180 MWe. B&W has been actively engaged with the NRC in working to move toward design certification and eventual commercial licensing.[54]

---

[54] See http://www.nrc.gov/reactors/advanced/mpower.html, accessed on May 31, 2015.

- The NRC has also been in discussions with NuScale Power (NuScale) about pre-application activities since 2008. NuScale is seeking to commercialize a modular, scalable 50 MWe iPWR design. It would have a 24-month refueling cycle and be fueled with 4.95 percent low enriched uranium.[55] This design and the mPower design would likely be commercially attractive primarily due to their basis in well-known LWR technology.

- As to non-LWR SMRs, GE Hitachi Nuclear Energy (GEH), for example, has been developing the PRISM design, which is a small, modular, pool-type, and sodium-cooled fast reactor with metallic fuel. The thermal power rating is 840 MWth. The NRC had actually done some related pre-application work on a similar design in the early 1990s. GEH has interacted with the NRC since 2010 with a draft licensing strategy. GEH touts the benefits of the capability to reduce the nuclear waste burden by consuming transuranic materials.[56]

- Toshiba Corporation is working on developing the Super-Safe, Small and Simple (4S) design, which is a small, pool-type, sodium-cooled fast reactor with metallic fuel. According to its designers, its comparative advantage is its suitability for remote locations to operate for 30 years without refueling. The 4S has two power rating modules: 10 MWe or 50MWe.[57] The NRC and Toshiba began discussions in 2007 about pre-application activities.

- KAERI has been moving forward with its SMART (system-integrated modular advanced reactor) technology, marketing it to clients in the Middle East in particular because the SMART reactor offers desalination as a comparative advantage.[58] SMART can deliver either 100 MWe electric power or 90 MWe with concurrent 40,000 tons of desalinated water for up to 100,000 residents. The designers have blended a mixture of new innovative design features for passive safety with well-proven PWR technologies. They believe that this hybrid approach will make SMART economically competitive because it has the best of new and old design principles. Also, they underscore the system simplification, modular construction, and reduced construction time as other comparative advantages.[59] On July 4, 2012, after a thorough review, the Korean Nuclear Safety and Security Commission granted design approval to SMART.

---

[55] See http://www.nuscalepower.com/our-technology/technology-overview, accessed on May 31, 2015.
[56] See http://gehitachiprism.com/what-is-prism/, accessed on May 31, 2015.
[57] See http://www.toshiba.com/tane/products_4s.jsp, accessed on May 31, 2015.
[58] Chen Kane and Miles A. Pomper, "Reactor Race: South Korea's Nuclear Export Successes and Challenges," Korea Economic Institute of America, Report, May 2013.
[59] Keung Koo Kim et al., "SMART: The First Licensed Advanced Integral Reactor," *Journal of Energy and Power Engineering*, 8 (2014) 94-102.

Regulatory Requirements for Licensing and Constructing Advanced Nuclear Energy Systems

In response to an order from the U.S. Congress, the U.S. Nuclear Regulatory Commission in August 2012 published a detailed report that discusses the status of the agency in preparing for potential licensing of advanced nuclear energy systems and the additional needs of the agency to meet the foreseeable future licensing applications. Significant issues that will affect certification and licensing of advanced nuclear energy systems are highlighted below.

The NRC report lays out four timeframes:

I. "Within the near term, in addition to current and planned Generation III+ licensing activities, the NRC anticipates licensing activities focused on integral pressurized-water reactor designs;

II. Within the longer term, the NRC anticipates continuation of the near-term activities and expanded activities pertaining to liquid-metal cooled reactor designs;

III. Within the horizon timeframe, licensing activities to continuation of those from the prior timeframes, may include one or more advanced reactor concepts currently identified for research by the Generation IV International Forum and supported by DOE; and

IV. For the beyond-the-horizon timeframe, NRC licensing activities would correlate with (1) the DOE's Nuclear Energy Research and Development Roadmap—Report to Congress, issued April 2010, (2) recommendations of the Blue Ribbon Commission on America's Nuclear Future—Report to the Secretary of Energy, issued January 2012, and (3) U.S. national policy regarding the nuclear fuel cycle."[60]

The NRC is geared primarily toward evaluating and licensing LWR-type reactors. The more that a reactor's design deviates from an LWR-design, the more time and resources (personnel, simulations, and testing facilities) the NRC will need to make a proper evaluation. It is important to recognize that the NRC's role is safety and not promotion of nuclear technologies. The NRC favors a "go-slow-and-steady" approach that proponents of new nuclear technologies could consider too cautious. But the NRC has to make sure that a thorough review is done in order to fulfill its charter of protecting the public. Thus, the NRC's report to Congress highlights the important requirement for vendors to submit as complete technical documents as possible and to answer all questions from the NRC in a thorough manner. Vendors, however, are concerned that the application costs are very high—and could end up being several hundred million dollars. The DOE has set aside some funds for regulatory financial support to help mitigate the high costs. But many vendors still have concerns about the prohibitive costs.

---

[60] U.S. Nuclear Regulatory Commission, "Report to Congress: Advanced Reactor Licensing," August 2012, p. v.

In addition to having to allocate more resources to understand designs that are significantly different from LWR designs, the NRC flags the following as a crucial issue: "The consideration of review and oversight of new nuclear fuel designs and their production. Any advanced reactor design that uses fuel that differs significantly from the current type (zirconium-clad, low-enriched uranium dioxide) will require the evaluation of technical and regulatory approaches to the licensing of fuel fabrication, transportation, storage, and waste disposal operations."[61] Thus, the NRC will have more scrutiny for different fuel types and processes other than typical LWR fuels.

The NRC also raises concerns about its international reputation. The NRC report explicitly mentions that its standards are often viewed as "the gold standard." Therefore, the NRC wants to maintain its credibility and the subtext is that if it is not careful in evaluating and licensing advanced nuclear energy systems, it could jeopardize this stellar reputation.

The NRC has specified three major components in order to be ready for high quality evaluation of advanced nuclear designs: (1) regulatory structure; (2) research efforts; and (3) human resource development. The first component will require significant reliance on the MDEP approach. The MDEP is the Multinational Design Evaluation Program of the Nuclear Energy Agency, a body of 14 countries' regulatory agencies that work to harmonize their efforts in considering the regulatory issues involved with advanced nuclear energy systems (as well as *Generation III* and *III+*).[62] In pursuing international engagements, the NRC would maintain interaction with DOE and the domestic industry to ensure broad stakeholder input regarding the technologies, licensing and operating experience, and overall safety philosophy.

"To address research efforts, NRC envisions working closely with DOE, the Electric Power Research Institute, the Nuclear Energy Agency, IAEA, and the nuclear industry to motivate, manage, and co-fund the research efforts, including unique facility development needed to support development and licensing of advanced reactor technologies. … The NRC will remain mindful of the need for clear independence in the regulatory aspects of these research endeavors by ensuring development of a clear and defensible set of research results to support regulatory decisions.

"Regarding human resource requirements, NRC envisions coordinating its efforts with DOE, the domestic nuclear industry, and academia, to support national programs of classroom, laboratory, and field experience, funded in part by the NRC Educational Grants Program, which would support development, licensing, construction, and operation of nuclear power plants and the associated fuel fabrication facilities. To the extent that interaction with international programs would facilitate the NRC's mission to protect public health and safety and the common defense and security in the licensing and oversight of new reactor technologies and fuel facilities, our plans would include those interactions. For advanced technologies, the NRC expects that coordinated programs led by DOE and the industry would support the NRC's skill needs for advanced reactor technologies."[63]

---

[61] Ibid, p. v.

[62] See https://www.oecd-nea.org/mdep/, accessed on May 31, 2015.

[63] NRC Report to Congress, August 2012, pp. vi-vii.

Knowledge Management, Knowledge Creation, and Training of the Workforce

The NRC and other regulatory agencies recognize the critically important issue of knowledge management (KM) "as a means of building and maintaining needed critical skills." The NRC, in particular, has "implemented three enterprise-wide KM initiatives in this regard: (1) identifying high-value/high-risk (of loss) knowledge and skills the staff currently possesses; (2) capturing and sharing that high-value/high-risk knowledge with other agency staff before it is lost; and (3) identifying high-value opportunities for creation of Communities of Practice that enable the sharing of knowledge and skills among those employees who perform the same job function… Other ways the agency is ensuring that critical skills are available in the future include the Grants Program and the Graduate Fellowship Program."[64]

The advanced nuclear energy systems of the future will require highly qualified and skilled people to operate and manage them. Unfortunately, the aging nuclear workforce presents a major challenge to bridging the gap between the generations. New nuclear construction in certain countries such as China and Korea has helped address this problem that is growing in the United States and much of Europe. In the United States, DOE in recent years has invested tens of millions of dollars into programs to motivate the next generation to become involved in cutting edge R&D in advanced nuclear energy systems. Notably, in the past year, the DOE through the Nuclear Energy University Program (NEUP) has awarded more than $30 million "to support 44 university-led projects aimed at developing innovative technologies in the areas of fuel cycle R&D, reactor concepts research, development, and demonstration, and advanced modeling and simulation. These NEUP projects will be headed by 30 universities in more than 20 states."[65] There are about 30 university nuclear engineering programs throughout the United States. In addition, another $20 million is set aside for five integrated research projects that focus on high priority research challenges with the lead teams at the Georgia Institute of Technology, MIT, Pennsylvania State University, the University of South Carolina, and the University of Wisconsin. Moreover, DOE has awarded more than $11 million to 12 research and development projects led by U.S. universities, DOE national laboratories, and industry in support of the Nuclear Energy Enabling Technologies Crosscutting Technology Development Program.

The United States is not the only country that recognizes the importance of knowledge management, the creation of new knowledge, and the preparation of the nuclear industry's workforce. The Republic of Korea has leveraged its top priority attention to this set of educational issues in its capability to offer a comparative advantage in training the workforce for the four power reactors under construction in the United Arab Emirates. The KAERI Nuclear Training and Education Center (KNTC) has been a leading center for four decades in elevating the Korean nuclear workforce to meet Korean national goals of achieving "national self-reliance" as well as cooperating with international partners in helping train other countries' nuclear workers.[66] Regarding knowledge management in the area of fast

---

[64] Ibid, p. 34.

[65] "DOE invests $67 million to advance nuclear technology," *Nuclear News*, October 2014, p. 88.

[66] See http://www.kntc.re.kr/english/about/introduction.jsp, accessed on May 31, 2015.

neutron reactors, India has an extensive program based at the Indira Gandhi Centre for Atomic Research. In addition to its domestic training and knowledge acquisition and preservation, this center is coordinating with the Fast Reactor Knowledge Organization System (FRKOS) being established with the IAEA. "FRKOS consists of an electronic repository of FR knowledge and experience from various countries with facilities for effective search and knowledge mining."[67]

Through these cooperative educational activities and knowledge sharing, advanced nuclear energy systems could make improvements much faster than if each country acted independently.

---

[67] K. K. Kuriakose et al., "Knowledge Management in Fast Reactors," *Energy Procedia*, 7 (2011) 672-677.

Conclusions: What Needs to be Done for Making Further Progress?

While there is excitement about the potential for commercialization of advanced nuclear energy systems, much more remains to be done for these technologies to be adopted by the market and then rise to widespread deployment. The review nature of this report has identified major themes and lessons learned from development of LWR technology and previous efforts on non-LWR technologies. Instead of repeating findings from the executive summary, the following are important issues to bear in mind during the next ten to twenty years:

- Government support is essential for new nuclear energy technologies. The level of support offered to date in the United States is likely not adequate to help these technologies cross from R&D to demonstration and deployment. Potentially several billion dollars will be needed. Utilities tend to be risk-averse especially on projects that can cost well over $1 billion.

- International cooperation is vitally important in R&D and demonstration. While GIF has provided a useful platform, it is likely that even more cooperation is needed bilaterally and multi-laterally due to the complex challenges of many of these technologies. In particular, although there has been bilateral cooperation between the United States and other countries that use nuclear energy, such as Korea and Japan, on R&D for advanced nuclear systems, these partnerships need to be strengthened and deepened beyond the current scopes of work. For example, within the next five years, the study examining pyroprocessing and fast reactors between KAERI and Argonne National Laboratory and Idaho National Laboratory will be concluding; assuming that this feasibility study shows promise for this technology, follow-on work would need to progress to the next stage of building prototypes and then move toward demonstration of a commercial-scale system. Governments in partnership will have to commit to funding at the several billion dollar level to advance a promising technology toward commercial demonstration. Cost-sharing between governments can help reduce the overall financial load for each government.

- Continued and expanded effort on multinational regulatory work is needed to harmonize regulatory standards and to meet high standards across all nuclear power countries that would help with widespread deployment of new nuclear technologies. International cooperation is also essential in safeguards by design to move toward more proliferation-resistant systems.

- Small, modular reactors look promising, especially those technologies that offer long-lived reactor cores, multiple modes of power generation, water desalination, industrial heat, and hydrogen production. These multi-operational modes can help even larger-sized power reactors make the economic case for their deployment.

- Energy efficiency will be a major determining factor for these new technologies. The more that they can provide energy conversion efficiencies greater than 40 percent the more likely they could compete with natural gas-power plants. In addition, nuclear plants that can offer base load electricity coupled with the capability to switch to load following or peaking power modes can further differentiate themselves in the marketplace.

- Governments and industry need to make adequate investments in knowledge management, knowledge creation, and training for the next generations of nuclear designers, builders, and plant operators.