The Future of Nuclear

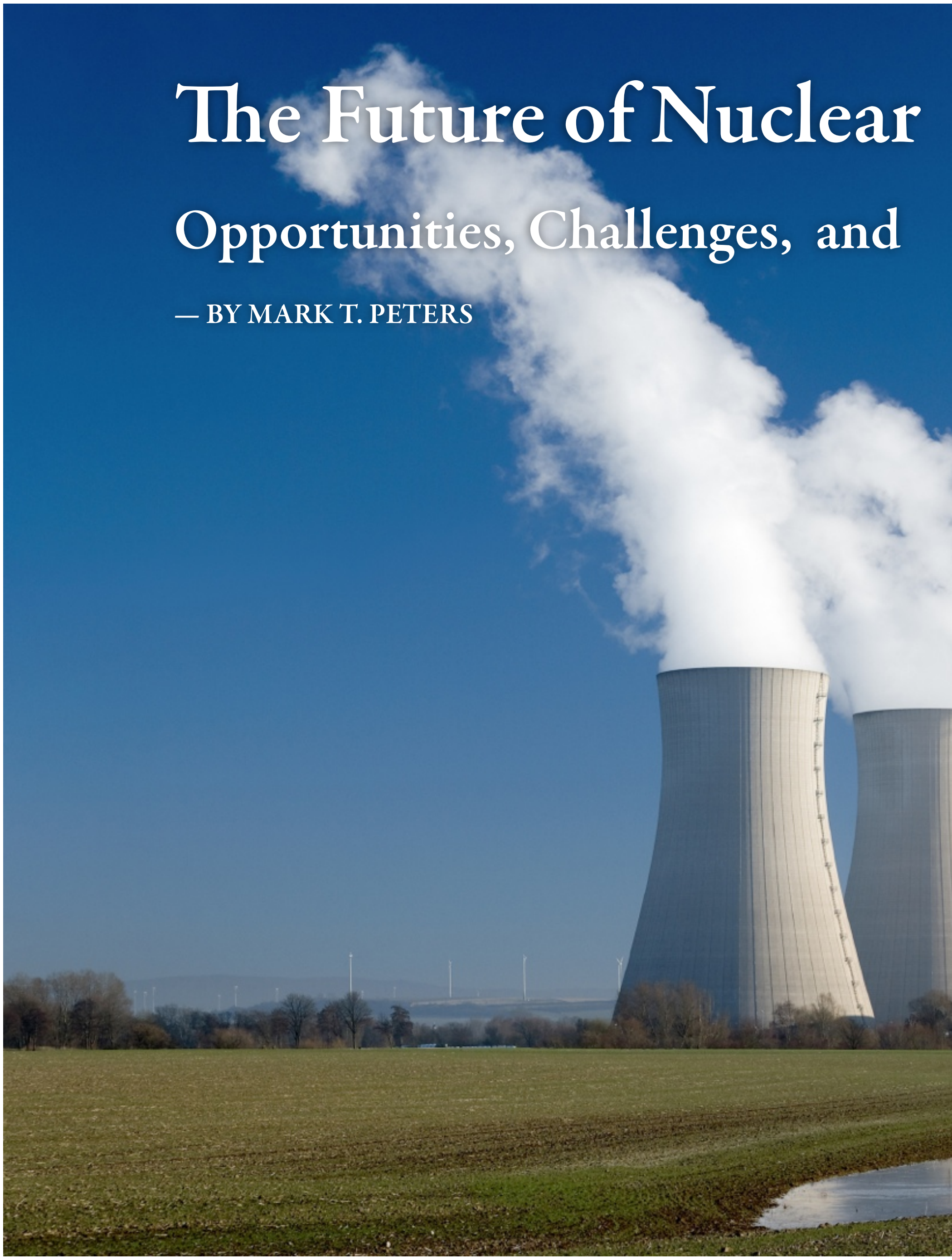
Opportunities, Challenges, and

— BY MARK T. PETERS

Since the late 1970s, when safety fears and economic factors converged to halt construction of new nuclear power plants, the nuclear energy industry has stalled in the United States. Meanwhile, other nations have made substantial investments in new nuclear power plants and advanced nuclear energy technologies. Today, however, the soaring cost of petroleum, increasing concerns about carbon emissions, and the aging nuclear power plant fleet have revived the national conversation on nuclear energy in America.

The Obama administration has signaled its willingness to support America's nuclear energy industry through additional loan guarantees for new plant construction. In his 2011 State of the Union address, President Obama set a goal of generating 80 percent of America's electricity from clean energy sources by 2035, and he included nuclear energy in his list of clean sources.

However, these positive signals from the White House must be balanced against some important hurdles: The events at the Fukushima Daiichi plant have reopened questions about operating safety; the relatively low price of electricity makes the substantial upfront costs of new nuclear power plant construction difficult to justify in the short term; the availability of plentiful, affordable natural gas reserves undercut the perceived future need for expanded nuclear power generation capacity; and last year's decision to withdraw the license application for a high-level nuclear waste repository at Yucca Mountain leaves open the continuing problem of providing safe, permanent disposal for America's legacy, current, and future nuclear wastes. Despite these short-term hurdles, the need to address the challenges of energy security and climate change, combined with continued robust safety, security, and oversight of existing plants and development and deployment of next-generation technologies, should strengthen and expand the role of nuclear energy in America's 21st-century energy portfolio.



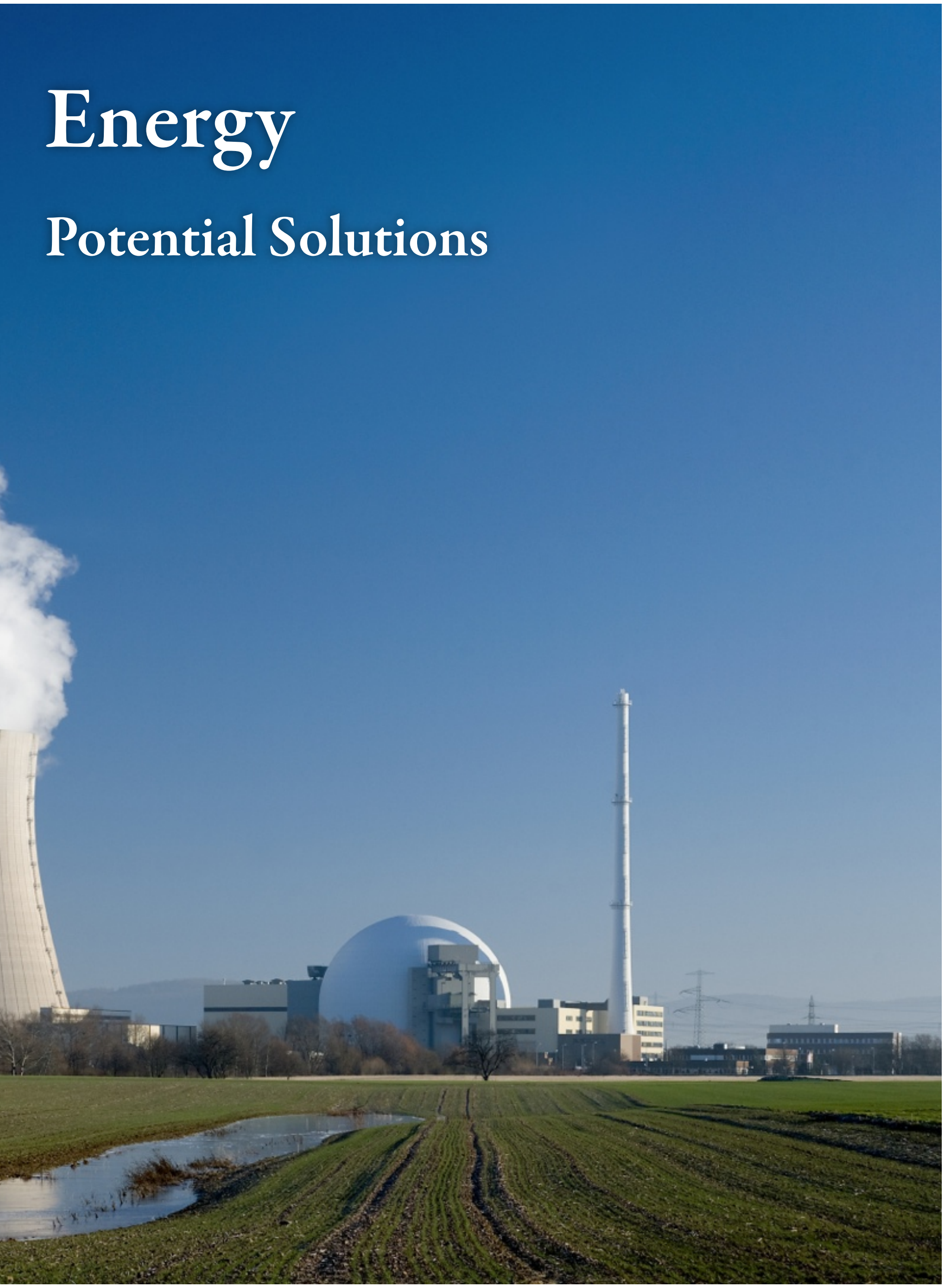
NUCLEAR ENERGY SINCE THE LATE 1970s

Although the power of the "peaceful atom" was initially welcomed as a generation source that would provide electricity "too cheap to meter," the economics of the industry were upended after the oil crisis of 1973-74. With the national economy stagnant and interest rates as high as 20 percent, the cost of building new nuclear capacity spiked from an average of $161/kW in 1968-1971 to $1,373/kW in 1979-84.[1] During the same period, U.S. environmentalists and other opponents of nuclear energy were galvanized by the highly publicized partial core meltdown at the Three Mile Island plant in Pennsylvania, which caused the release of

[1] *Nuclear Assessment,* by Charles K. Ebinger and John P. Banks, the Energy Security Initiative at the Brookings Institution. April 30, 2010. http://www.brookings.edu/articles/2010/0430_nuclear_energy_banks_ebinger.aspx.

Energy

Potential Solutions



small amounts of radioactive gases. The combination of extraordinary costs and public opposition brought U.S. nuclear power plant construction to a halt. After 1978, no new units were ordered for more than 30 years,[2] although power uprates and license extensions for many existing plants have been granted since then. (Work began recently on preparation for new reactors at the Vogtle nuclear plant site in Georgia; the Nuclear Regulatory Commission (NRC) is expected to issue the combined construction and operating license for the new reactors by the end of this year.)

The environmental and economic tradeoffs that have resulted from the national decision to halt investment in new nuclear power plants in the United States were predicted with some accuracy by a number of researchers, including nuclear scientist Alvin M. Weinberg, then director of the Institute for Energy Analysis in Oak Ridge, TN, and the former director of Oak Ridge National Laboratory. In his article “Is Nuclear Energy Necessary?” published in *The Bulletin of the Atomic Scientists* in March 1980, he cautioned that a moratorium on new nuclear plants would “place great pressure on coal or imported oil, or both,” and would raise the specter of a “carbon dioxide catastrophe.”[3]

Three decades later, the imminent risks of climate change have become increasingly apparent. The developing understanding of the true “cost of carbon” includes a better understanding of the widespread – if not immediately visible – health impacts of greenhouse gas emissions. For example, coal-fired generating plants emit large volumes of particulates and fly ash; a 2009 report by the Clean Air Task Force estimated that 13,200 people in the United States would die prematurely in 2010 from fine particle pollution emitted by coal plants. Those premature deaths represent huge financial costs in terms of healthcare-related expenses and lost productivity. When we factor in the hidden social costs of carbon emissions, we gain a new perspective on the economics of new nuclear power plant construction.

By 2030, most existing nuclear power plants in the United States will reach the end of their 60-year operating licenses. At present, it is unlikely that renewable energy sources, such as solar, wind, water, and geothermal energy, will be sufficient to replace that reliable, base load capacity when those nuclear plant licenses expire. The United States must devise an economically viable plan for more nuclear power plants, which now produce nearly 20 percent of U.S. electricity.[4]

[2] *Nuclear Assessment,* by Charles K. Ebinger and John P. Banks, the Energy Security Initiative at the Brookings Institution. April 30, 2010. http://www.brookings.edu/articles/2010/0430_nuclear_energy_banks_ebinger.aspx.

[3] “Is Nuclear Energy Necessary?” by Alan Weinberg, *Bulletin of Atomic Scientists*, March 1980 p. 34.

[4] “A Lifetime of Service: Safely Operating Nuclear Power Plants for 60 Years or Longer,” U.S. Department of Energy, Office of Nuclear Energy. (print brochure) http://www.ne.doe.gov/pdfFiles/NE_Trifold_LifetimeofService_Web.pdf

AMERICA AND THE NEXT GENERATION OF NUCLEAR REACTORS

In looking at the possibility of a "nuclear renaissance" in the United States, Americans can build on the experience of other nations. Today, 14 percent of the world's electricity is generated from nuclear energy, and 16 nations rely on nuclear energy to generate more than 20 percent of their electricity. France derives more than 75 percent of its electricity from nuclear energy and is the world's largest net exporter of electricity. In Asia, South Korea's 21 reactors provide almost 40 percent of the country's electricity. Japan has relied on nuclear energy for 30 percent of its electricity; however, the events at Fukushima Daiichi may change the Japanese situation, as the accident has taken at least four reactors permanently off-line. China has completed nine new nuclear plants in the past decade, with dozens more currently under construction.

Concerns about energy security and carbon reduction have reduced opposition to nuclear energy in a number of European countries. Last year, the Swedish Parliament voted to allow replacement of reactors at 10 nuclear power plants, reversing a 1980 referendum that called for their eventual phase-out. In July 2010, the Finnish Parliament approved construction of two nuclear power plants. Italy has ended a ban passed in 1987 and is actively considering sites for new plants.[5] Switzerland's citizens have allowed its moratorium on new plants to expire. In total, there are 195 nuclear power plant units operating in Europe, with 19 more units under construction.

Today, almost all currently operating nuclear power plants rely on light-water reactors derived from research done at Argonne National Laboratory in the 1950s and 1960s.[6] These reactors rely on water to cool the reactor and transport its heat to large steam turbines that generate electricity. Light-water reactors are fueled with uranium that has been processed, or "enriched," increasing the amount of the isotope uranium-235 it contains to 4 percent of its total weight. By contrast, uranium straight from the mine contains about 0.7 percent U-235, weapons-grade uranium is defined as 20 percent U-235, and military weapons designs are based on a U-235 content of 90 percent or more.

Although the basic designs for these light-water reactors are decades old, advances in nuclear technologies have improved efficiency and upgraded both equipment and fuel, enabling existing nuclear plants to increase electricity generation. In the United States, those technological improvements have made it possible to increase existing plants' electricity generation by 178 billion kilowatt hours (kWh)—equivalent to the output of 23 new power plants.

As we look to the future, new nuclear power plants built from next-generation designs can offer improved fuel technology, thermal efficiency and safety systems, longer operational life, and reduced construction and maintenance costs. The designs of these next-generation reactors, which are currently under construction worldwide, address many of the concerns about safety, proliferation, and waste disposal that have shaped public opposition to nuclear energy over the years.

SAFETY

It is important to put safety concerns about nuclear power in perspective. Certainly, the recent events at Fukushima, along with the accident at Three Mile Island and the Chernobyl disaster, have raised serious international concerns about nuclear plant safety. However, it should be remembered that Three Mile Island caused no deaths or injuries to plant workers or residents living nearby, and the incident led to tightened regulatory oversight by the U.S. NRC, as well as sweeping changes in worker training, emergency response planning, radiation protection, and many other areas of nuclear power plant operations. Ultimately, the accident led to improved design and enhanced safety in U.S. nuclear power plants.

The story of the Chernobyl disaster is, of course, far more troubling. The accident, which was caused by a sudden surge of power on April 26, 1986, destroyed a reactor at the nuclear power station at Chernobyl in the former Soviet Union, now Ukraine. The accident released massive amounts of radioactive material into the environment and claimed the lives of several dozen workers. The resulting contamination forced evacuation of nearly 350,000 people living within a 30-km radius of the plant. However, it must be noted that Chernobyl's reactor

[5] "Sweden Reverses Nuclear Phase-out Policy," *Issue Brief*, by Johan Bergenäs of the James Martin Center for Nonproliferation Studies at the Monterey Institute for International Studies. November 11, 2009. http://www.nti.org/e_research/e3_sweden_reverses_nuclear_phaseout_policy.html

[6] See PHOTO: http://www.flickr.com/photos/argonne/4460350224/ or http://www.flickr.com/photos/argonne/5039459604/ (historical).

was based on a Soviet design – using high-power, pressure-tube reactors, moderated with graphite and cooled with water – that has never been used in the United States.

United States. It also was operated without a containment shield, a design that would not be allowed anywhere in the world today. Although the Chernobyl experience was tragic, it also has helped the nuclear industry and its regulators to gain a fuller understanding of nuclear reactor safety. And overall, the world's 400-plus commercial nuclear reactors have logged an excellent safety record.

Recent events at the Fukushima Daiichi nuclear power plant, due to the earthquake and tsunami in Japan on March 11, 2011, are very concerning. The nuclear power industry and regulatory authorities, both in America and internationally must respond to this by further improvements in reactor safety systems, wet storage systems for spent nuclear fuel, and emergency response. (Note: At the time this article was submitted for publication, the earthquake and tsunami in Japan had only just occurred. More information will, of course, shed light on safety issues for the future.)

In the nuclear plants currently operating in the United States, reactor safety has been based on a "defense-in-depth" approach, using a diverse set of safety measures that include many layers of reinforced physical barriers, including thick steel and concrete walls around the reactor that are built to withstand tornado-strength winds, earthquakes, and aerial aircraft assault. American nuclear plants also are protected by control systems designed with multiple back-ups.[7]

The newer generations of advanced reactors include additional fail-safe measures, including improvement in emergency core cooling systems. Areva, a French company, is building the European Pressurized Water Reactor, which increases the number of emergency core cooling systems from two to four. The extra cooling systems provide increased safety and also allow the plant to keep running while one of the systems is down for maintenance.

Wherever possible, "active" systems that are dependent on pumps, valves, and human operators are replaced by "passive" systems that use natural forces, such as gravity and convection, to respond to malfunction. For example, in next-generation designs, the reactor may be engineered so that, if core temperature rises above normal levels, the efficiency of the fission reaction decreases and it slows down automatically. Control rods that stop the nuclear reaction can be suspended above the reactor and held in place with electricity, so that any interruption to the station's electrical power will automatically insert the rods into the reactor. Also, any closed loop with a heat source at the bottom and cooling on top will develop a flow that sends the heated stream rising to the top and the cooled stream to the bottom. Called "natural circulation", this allows coolant to move in the core without the aid of pumps. This means that if the plant loses power, as happened at the Fukushima Daiichi plant in Japan, the reactor does not require electricity to cool the core after shutdown.

Westinghouse's next-generation AP1000 design, which features a number of "passive" safety systems, requires only half as many safety-related valves, one-third fewer pumps, and 83 percent fewer safety-related pipes than the company's currently operating reactors.[8] The reduced need for pumps and controls means that next-generation reactors can improve safety performance while costing less to construct and operate.

[7] U.S. Department of Energy, Department of Science. http://www.er.doe.gov/bes/reports/files/ANES_rpt_print.pdf.
[8] "AP1000 at a Glance," Westinghouse: http://www.ap1000.westinghousenuclear.com/ap1000_glance.html.

PROLIFERATION

Advances in nuclear energy technology also are addressing concerns about proliferation – the possibility that fuel for nuclear reactors could be converted to weapons-grade materials through enrichment or reprocessing. These concerns date back to 1974, when India exploded a nuclear device using plutonium produced in a research reactor. Canada had manufactured the heavy-water research reactor, and the United States had provided the heavy water. In addition to heavy-water reactors, fast reactors, which offer a "closed" fuel cycle, have prompted misgivings about the diversion of that technology for nuclear weaponry. Fast reactors – so-called because they are cooled by a liquid metal, such as sodium, that slows the movement of neutrons in the reactor's core less than a moderator such as water – actually can produce more fuel than they consume. Theoretically, fast reactors and a closed fuel cycle (full recycling) could use nearly all of the energy available in uranium (see discussion below).

Before it can be recycled, a reactor's used fuel must go through an aqueous or electrochemical process, which also could be used to separate out weapons-grade plutonium from the spent nuclear fuel. The danger of nuclear weapons proliferation prompted President Jimmy Carter to ban reprocessing for commercial purposes in 1977, although it is still used in France, Japan, Great Britain, and other countries that rely on stringent security procedures to protect the products of reprocessing. In 1981, President Ronald Reagan lifted the ban, but the business case for commercial reprocessing no longer existed in the United States. In 2001, the George W. Bush administration revisited the issue of developing forms of reprocessing that would decrease proliferation risk by not separating pure plutonium.

In exploring reprocessing methods for reducing proliferation risk, U.S. scientists and engineers have developed new techniques, including pyroprocessing, which uses electric current to separate fission products from the heavier uranium, plutonium, and other actinides.[9] The fission products, which remain radioactive for millennia, are removed for permanent disposal. The remaining radioactive materials are recast into fresh fuel rods. Pure plutonium – a critical component of most nuclear weapons – is never separated out during pyroprocessing. The resulting fuel materials are highly radioactive and are extremely difficult to handle without specialized equipment and facilities. Pyroprocessing facilities can be built directly on fast reactor sites, reducing transportation of dangerous materials and the associated risk of diversion. Reprocessing of spent reactor fuel also could dramatically reduce the need for uranium mining and enrichment, lessening the risk that militant groups or terrorists could acquire uranium enrichment technology.[10]

The challenge of nuclear waste management has become more pressing in the United States.

THE CHALLENGE OF NUCLEAR WASTES

The challenge of nuclear waste management has become more pressing in the United States, from a policy perspective, since the 2009 decision to halt operations at Yucca Mountain. Given advanced technologies that limit the risk of proliferation, closing the fuel cycle could offer a workable solution to the challenge of nuclear waste management. A closed fuel cycle would greatly limit the amount of radioactive waste generated by a given reactor: Where a commercial light-water reactor produces about 20 metric tons of waste per year, a fast reactor with the same power output creates one metric ton of waste. The resulting waste can be shaped into more stable forms, such as a solid vitrified glass, for long-term disposal. Because it is less radioactive, this waste generates less heat and can be stored more compactly than waste from light-water reactors. Ultimately, fast reactors could also allow reprocessing of waste from light-water reactors currently in operation.

In contrast with fast reactors in a closed fuel cycle, light-water reactors are highly inefficient in their use of uranium, consuming only about 5 percent of the available energy before the fuel becomes contaminated with other isotopes and must be discarded. This spent fuel, which is highly radioactive, is currently stored on site at each nuclear reactor. Two storage methods are used: Waste must cool in a pool to reduce heat, and then can be moved to dry-cask storage, sealed in steel and concrete tanks surrounded by inert gas. Spent nuclear fuel is currently stored in pools and dry casks at sites across the country.[11] Ultimately, these wastes will require reprocessing or disposal in a geologic repository for many thousands of years.

Despite the long-term advantages of the closed fuel cycle, the extra cost it imposes has served as a disincentive to widespread adoption of fast reactor and advanced recycling technologies. In Europe, reprocessing has generally added 5 to 6 percent to the cost of producing electricity.[12] Given that fresh uranium remains plentiful and inexpensive -- the price of uranium accounts for only 2 to 4 percent of the price of electricity – the added cost of nuclear fuel reprocessing has been viewed as prohibitive.

[9] Argonne scientists conduct research on minimizing waste from reactors. PHOTO: http://www.flickr.com/photos/argonne/4074828015/.

[10] "Smarter Use of Nuclear Waste," *Scientific American*, Hannum, Marsh and Stanford. Dec. 2005.

[11] Cooling cores at Idaho National Laboratory. PHOTO: http://www.flickr.com/photos/argonne/3954062594/.

[12] Testimony by Dr. Alan Hanson, Areva, before the U.S. House Science & Technology Committee, June 17, 2009.

However, the combined effect of the costs for spent fuel management from light-water reactors and need for sustainable use of uranium resources could alter the financial equation and make fuel reprocessing and closing the fuel cycle viable.

ECONOMICS

Currently, the estimated cost of construction of a twin-unit nuclear power plant is uncertain, but is several billion dollars to as much as $10 billion. By any measure, those costs are substantial, and it can take a decade for a new plant to be designed, approved, built, permitted, and brought online. Due to delays and cost overruns on nuclear plants in the 1980s and 1990s, many private U.S. investors have been reluctant to invest in new power plants. Although 2007 saw a resurgence of interest in the private sector, the discovery of vast new reserves of natural gas in the United States has made less-expensive gas-fired power plants more attractive to investors.

However, most cost comparisons between natural gas and nuclear energy fail to address the full environmental cost of carbon emissions. Although natural gas burns more cleanly than coal, it is not carbon-neutral. The U.S. Department of Energy estimates that every megawatt-hour of electricity produced by conventional coal-fired technology produces 1 metric ton of CO_2; generating a megawatt-hour of electricity through natural gas produces 0.6 metric tons of CO_2.[13] (This means that, each year, American nuclear plants avert the release of almost 800 million tons of CO_2 into the atmosphere.[14]) The imposition of a clean energy standard, carbon taxes, or cap-and-trade incentives could substantially reduce the economic advantage of natural gas over nuclear power.[15]

Over the past two years, the Obama administration has shown strong support for nuclear energy. Last year, the White House announced $8 billion in federal loan guarantees for construction of two new conventional reactors at the Vogtle site in Georgia, and President Obama's proposed 2012 budget would triple the amount available for nuclear power plant construction loan guarantees.[16] The NRC also is reviewing applications for about 30 new reactors.[17]

There are a number of technological and procedural options that could reduce the cost of nuclear power plant construction. For example, upfront capital costs could be reduced by adoption of general design standards, which would allow utilities to choose from an array of pre-approved, standardized plant designs. Such an initiative is currently under-way in the United States and should make it possible for newer, advanced reactor designs to come online later this decade.

The combined effect of the costs for spent fuel management from light-water reactors and need for sustainable use of uranium resources could alter the financial equation and make fuel reprocessing and closing the fuel cycle viable.

Costs could also be reduced by using small modular reactors (SMRs) as an alternative to conventional light-water reactors. Components for these scaled-down reactors, which are about one-third the size of current power plants, could be built on assembly lines in advanced factories instead of more expensive on-site construction. President Obama's proposed 2012 budget would invest $500 million in SMR research and technology over the next five years. These small reactors could replace aging coal-fired power plants that already are served by grid connections, reducing costs even further. Estimates of the cost of building an SMR have ranged from several hundred million dollars to as much as $2 billion. The units could benefit initially from a built-in initial market at federal sites facing an executive order to reduce carbon footprints by 28 percent by 2020.[18] However, the cost per KW of SMRs will be higher than larger plants in the early stages of deployment. Nonetheless, given their lower initial costs, SMRs could prove more attractive to private investors, with time, than full-sized nuclear power plants. The combination of regulatory reform, federal loan guarantees, and lower upfront costs for smaller reactors could help to make nuclear power cost-competitive with gas and coal.

Going forward, federal investment in fundamental nuclear science and engineering research could help to bring improved reactors and better fuel recycling technologies to the market. Given our long track record of expertise and success in nuclear engineering, Argonne and our sister national laboratories are well positioned to lead basic scientific research, translational research, and applied engineering in nuclear energy generation and advanced nuclear fuel cycles. Already, we are using our experimental and supercomputing capabilities to enable improved operation of existing reactor plants,[19] and create affordable and efficient designs of future-generation nuclear energy systems. We also are using the expertise derived from our broader nuclear energy capabilities to develop new non-proliferation strategies and tools, including conversion of research reactors to low-enrichment fuels, technology export control, risk and vulnerability assessments, and information systems.

[13] "Nuclear Energy Research & Development Roadmap," Report to Congress, U.S. Department of Energy. April 2010. http://www.ne.doe.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf, p.20

[14] 798.74 billion kilowatt-hours = 798 740 000 megawatt-hours * 1 metric ton CO2 saved per megawatt hr (figure from Energy Information Administration). http://www.eia.doe.gov/ask/electricity_faqs.asp#nuclear_generation)

[15] "The Future of the Nuclear Fuel Cycle", an Interdisciplinary MIT Study, Massachusetts Institute of Technology, 2010. http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle.pdf p.19

[16] "Obama Would Triple Guarantees for Building Nuclear Reactors," *Bloomberg News*, February 14, 2011: http://www.bloomberg.com/news/2011-02-14/obama-would-triple-guarantees-for-building-nuclear-reactors.html

[17] "Expected New Nuclear Power Plant Applications," Nuclear Regulatory Commission, April 13, 2011: http://www.nrc.gov/reactors/new-reactors/new-licensing-files/expected-new-rx-applications.pdf

[18] "Administration to Push for Small 'Modular' Reactors," *New York Times*, February 13, 2011: http://www.nytimes.com/2011/02/13/science/earth/13nuke.html

[19] Simulation of a nuclear reactor subassembly, created on Argonne's supercomputer, the Blue Gene. PHOTO: http://www.flickr.com/photos/argonne/4192798645/.

CONCLUSION

In July 2011, the Department of Energy's Blue Ribbon Commission on America's Nuclear Future is scheduled to deliver its draft conclusions on the best strategies for U.S. nuclear waste management. This report, along with the proposal by the Obama administration to create a clean energy standard, should serve as the opening for a new national conversation on nuclear energy and nuclear waste management policy. Certainly, there are many concerns that must be addressed. However, advances in nuclear technology have significantly altered the cost-benefit equation that led the United States to interrupt its significant investment in nuclear power three decades ago.

National consumption of electricity is large and growing, and the majority of usage in homes, schools, hospitals, and businesses requires a steady, reliable, around-the-clock power supply.[20] At present, solar and wind energy provide intermittent energy, and we must rely on nuclear- or coal-generated power to provide base load electricity when the sun isn't shining and the wind isn't blowing. Although widespread use of electricity generated by renewable sources remains an important goal, it may take up to 20 years to develop cost-effective, scalable energy storage and grid technology that would make that goal a reality.

U.S. Energy Secretary Chu has stated: "Nuclear energy provides clean, safe, reliable power and has an important role to play as we build a low-carbon future." As the nation's current and future energy options come under review, a new generation of nuclear power technologies can restart America's nuclear industry and assure an adequate, environmentally sound source of electricity for the decades to come. ■

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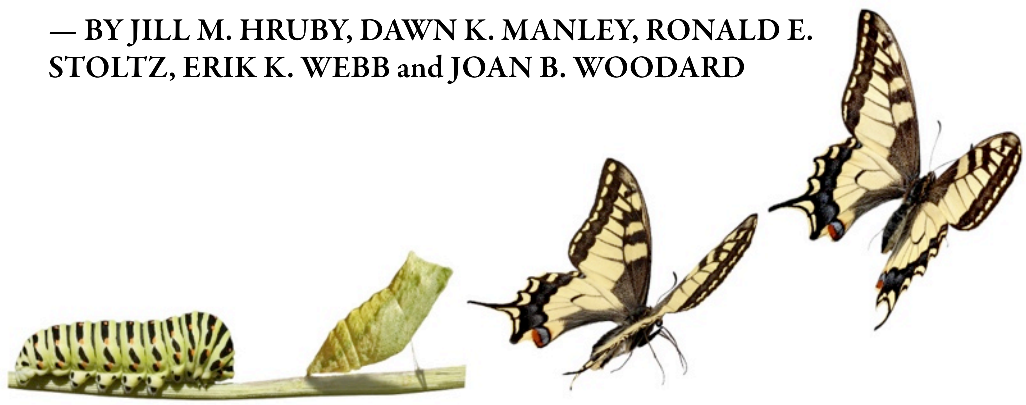
[20] "Myths and Facts About Nuclear Energy Supply," Nuclear Energy Institute: http://www.nei.org/newsandevents/nei-backgrounders/myths--facts-about-nuclear-energy/myths--facts-about-energy-supply

The Evolution of Federally Funded Research & Development Centers

— BY JILL M. HRUBY, DAWN K. MANLEY, RONALD E. STOLTZ, ERIK K. WEBB and JOAN B. WOODARD



INTRODUCTION

Federally Funded Research and Development Centers (FFRDCs) have thrived, struggled, and evolved to tackle national security missions for more than 70 years. FFRDCs were instituted in the early 1940s to mobilize the country's scientific and engineering talent. They came into national prominence during World War II and again during the Cold War as a mechanism to focus scientific and engineering expertise on pressing national security challenges that demanded intense, sophisticated, and sustained technical talent. Because of the urgency and complexity of their missions, creating and maintaining this body of top technical capability required flexibility and practices not available in the government.

Over the decades since their inception, FFRDCs have become more diverse both individually and collectively in response to expanding national security needs. The government has examined and reexamined their existence, charters, and mission. Today, the FFRDC system finds itself at a crossroad. The national security environment is more dynamic than ever, while simultaneously the budgetary pressures, government accountability, and federal workforce initiatives are forcing reviews of government contracting including FFRDCs.

This article reviews the characteristics of FFRDCS and describes how they have adapted to shifting national security needs and during intense periods of government scrutiny. Two recent incidents, the attempted airline bombing on Christmas Day 2009 and the Gulf of Mexico oil spill in 2010, serve as examples of challenges that relied on the technical expertise of the nation's FFRDCs. Each FFRDC should be held to high standards, and the collection of FFRDCs should be considered systemically, in order for the nation to be prepared to meet 21st century security challenges.