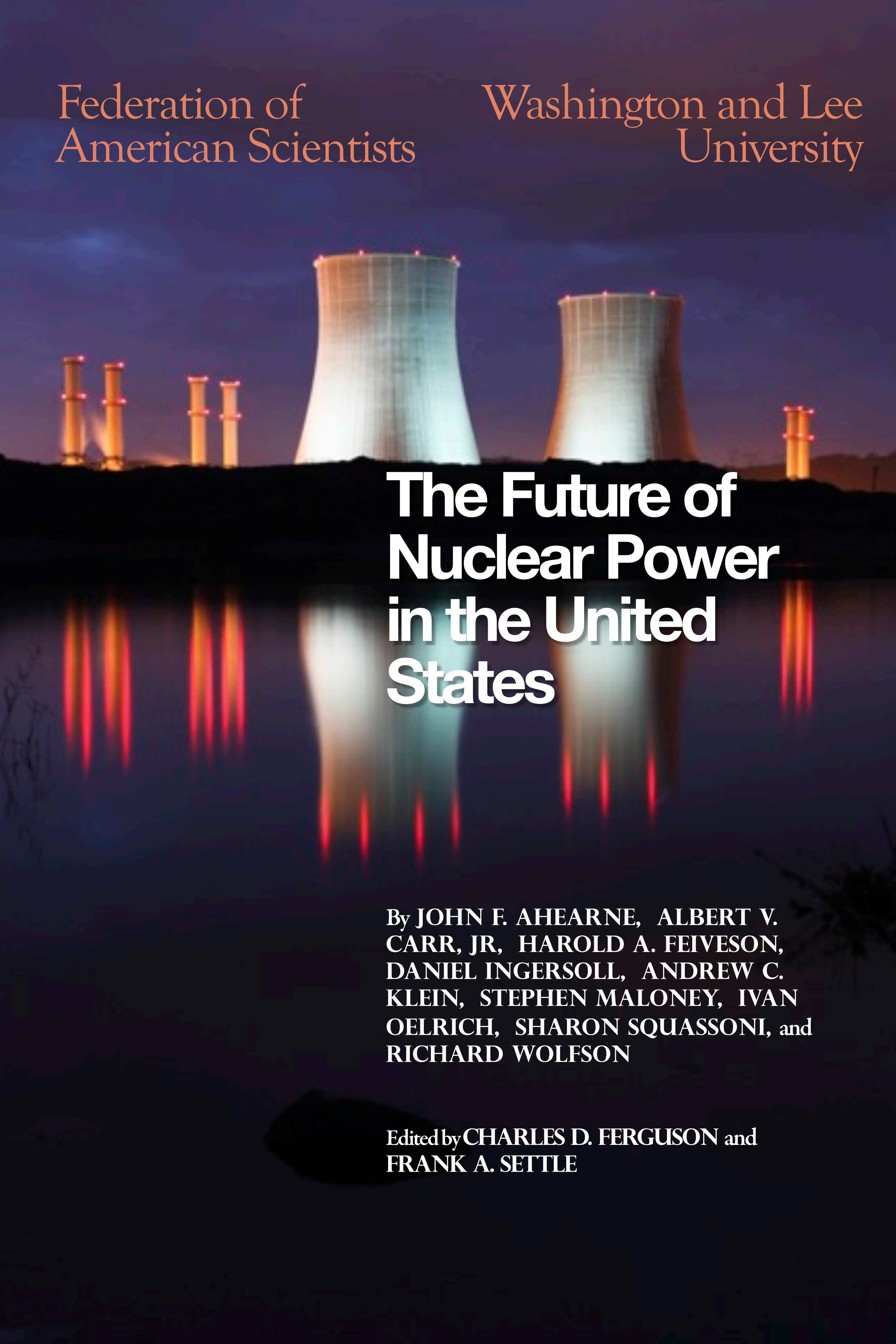


Federation of American Scientists

Washington and Lee University

The Future of Nuclear Power in the United States

By JOHN F. AHEARNE, ALBERT V. CARR, JR, HAROLD A. FEIVESON, DANIEL INGERSOLL, ANDREW C. KLEIN, STEPHEN MALONEY, IVAN OELRICH, SHARON SQUASSONI, and RICHARD WOLFSON

Edited by CHARLES D. FERGUSON and FRANK A. SETTLE

FAS and WASHINGTON and LEE UNIVERSITY

The Future of Nuclear Power in the United States

By John F. Ahearne, Albert V. Carr, Jr, Harold A. Feiveson, Daniel Ingersoll, Andrew C. Klein, Stephen Maloney, Ivan Oelrich, Sharon Squassoni, and Richard Wolfson

Edited by Charles D. Ferguson and Frank A. Settle

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 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 Special Reports are the sole responsibility of the author or authors.

About Washington and Lee University

Washington and Lee University, the nation's ninth oldest institution of higher education, is among the nation's premier liberal arts colleges and universities. Washington and Lee University provides a liberal arts education that develops students' capacity to think freely, critically, and humanely and to conduct themselves with honor, integrity, and civility. Graduates are prepared for life-long learning, personal achievement, responsible leadership, service to others, and engaged citizenship in a global and diverse society.

For more information about FAS or publications and reports, please call 1-202-546-3300, email fas@fas.org, or visit the website at www.FAS.org.

ISBN 978-1-938187-00-1

FOREWORD

In early 2010, when we began producing this report, we could not have predicted that one year later there would be a major accident at the Fukushima Daiichi Nuclear Power Plant in Japan in March 2011. Writing this foreword in February 2012, it is still too soon to know the full implications of this accident for the United States and the global nuclear industry. Instead of focusing on this issue, we, the principal investigators, will discuss the original motivations for this report. These motivations are still relevant regardless of the accident. If anything, the accident further underscores that constant vigilance is needed to ensure nuclear safety. The primary motivation is to educate policymakers and the public about where nuclear power in the United States appears to be headed in light of the economic hurdles confronting construction of nuclear power plants, the aging reactors (most of which were built more than 30 years ago), and the graying workforce (many of whom are nearing retirement age). A corollary motivation is to provide guidance to policymakers in their decisions about the complex subject of nuclear power.

To acquire sage advice, we asked a distinguished group of experts to provide their insights about the safety, security, building, financing, licensing, regulating, and fueling of nuclear power plants. These experts also addressed the issues of managing spent nuclear fuel and associated wastes, comparing nuclear energy to other energy sources, and assessing the potential commercialization of technologies such as small, modular reactors and Generation IV reactors.

Will nuclear power in the United States experience a revival in this and the following decade? It is too difficult to know at this time considering the complicated set of factors analyzed by this report's group of experts. We did not ask the group to reach a consensus. Instead, each author focused his or her expertise on a particular aspect of nuclear power.

Nonetheless, we believe that it is worth highlighting here some insights from the individual chapters. In the opening overview chapter, Sharon Squassoni assesses that "U.S. nuclear energy growth can only be achieved with a combination of aggressive government support and a complete revamping of the U.S. nuclear industry to stress standardization and modularization in construction. The best approach for the U.S. nuclear industry over the next five years will be to demonstrate that it can manage each stage of the licensing, construction, and operating processes of the first four [new] reactors competently and efficiently." Concerning the challenges of financing the new reactors, Stephen Maloney underscores the need for the United States to have a "viable bond market." He advises that these "markets require Federal Reserve policies, low corporate tax and capital gains rates, a strong currency, and stable growth," but the "deficit spending policies in place today do very little to create a viable bond market." Even if the financing risk were more manageable, licensing and regulating are two additional requirements that can pose significant challenges. Albert V. Carr, Jr. provides a masterful explanation of the U.S. history of licensing and regulating nuclear plants and is cautiously optimistic that a nuclear revival is underway given the recent applications for new licenses.

Nuclear power also has to meet high safety standards. John F. Ahearne examines the question of whether nuclear plants are safe enough and emphasizes that safety "remains a mixture of design, construction, maintenance, and what has been called a 'safety culture': the need for all involved personnel to stress safety in all their practices." Moreover, after "the two major reactor accidents of TMI and Chernobyl, designs have been scrutinized and improved, operating practices improved, and personnel training stressed," and that reviews of the Fukushima Daiichi accident "may spur further design changes and safety retrofits."

While safety relates to unintentional accidents, security depends on keeping nuclear plants protected against intentional attacks or sabotage. Harold Feiveson provides an in-depth analysis of the design-basis-threat (DBT), which is an assessment of the plausible threats that nuclear plants confront and must defend against, but he points out that despite improvements in the DBT after the 9/11 terrorist attacks, "questions remain whether the DBT is yet realistic enough to capture plausible threats by terrorist groups, and whether the DBT and associated reactor security operations have been adjusted to accommodate industry concerns with cost." Furthermore, "there will always be the possibility of a beyond-DBT attack on a reactor," and he consequently recommends that the industry pursue new reactor designs, reactor site locations, and operational procedures that would boost the inherent safety and security of the plants.

If nuclear power is to have a viable future in the United States, the plants will adequate supplies of fuel. Presently, U.S. nuclear power plants are fueled with uranium-based fuels. But in the future, they could use recycled plutonium for fuel. Ivan Oelrich addresses the reliability of uranium supplies and the possibility of a plutonium fuel economy. He concludes that "allowing for robust growth in nuclear-electric power generation and using fairly conservative assumptions about current and future reserves, decisions about building nuclear reactors should not today be constrained by concerns about fuel availability. The long-term fuel situation will be constantly reevaluated but, for decades to come, uranium availability will most likely not be the factor limiting nuclear growth." Concerning a plutonium economy, he determines that because of "the technical uncertainties, making an irreversible decision today is ill- advised and it is unnecessary. While there is universal agreement that some form of longterm waste repository will be required, wastes may not need to be committed to a repository right away. ... Pending resolution of questions regarding long-term geological storage or fuel for fast reactors, the plutonium can sit in the used fuel rods where it is safe from theft and cannot be used for weapons."

A robust supply chain and highly skilled personnel are needed to ensure the future of nuclear power in the United States. Andrew C. Klein points out the reality that the U.S. nuclear industry is embedded in an international supply chain. He underscores that "U.S. utilities and consumers of electricity will benefit from a competitive market for the supply of nuclear reactor systems, parts, and components. U.S. suppliers of these systems, parts, and components must be enabled to effectively compete if they are to remain strong participants in this market place." Regarding the future nuclear workforce, he discusses that competition "will come from various sectors, both inside and outside of the nuclear industry. The electric utility industry, including all means of production and distribution of electricity will look for similarly educated and trained personnel."

Further examining the theme of competition, Richard Wolfson analyzes the criteria from the perspectives of different groups of people for choosing nuclear energy compared to other energy sources. That is, consumers and businesses want cheap and reliable sources. "An environmentalist will value sustainability and minimal environmental impact—especially low carbon emissions," but would need to "smarten" the electricity grid in order to substitute wind and solar—intermittent sources—for nuclear energy, which can provide base-load power. "A state utility commissioner, concerned for stability in pricing and availability of future energy supply, might want to keep the low-cost energy from established nuclear plants in the mix." Wolfson also discusses whether alternative nuclear technologies " could "substitute for today's generation of light-water fission reactors." Such substitutes could include the potential for fusion or fusion-fission reactors and breeder reactors. But given the technical challenges of commercializing fusion and the "spotty operating records" of the handful of breeder reactors that have been built over the past several decades, he concludes that light water fission reactors will most likely be the nuclear technology of choice for decades to come. In considering alternative nuclear technologies, the report ends with Daniel Ingersoll examining Generation IV reactors and small, modular reactors. Given adequate government support for these emerging technologies to overcome financial and institutional challenges, he foresees these nuclear systems as major "components of the future energy portfolio."

As educators, we believe that this report will serve as both a useful tutorial for the general public and a guide for policymakers. The insights in the chapters will help further the necessary public debate as the United States wrestles with the formidable energy challenges in the future.

Charles D. Ferguson
President
Federation of American Scientists

Frank A. Settle
Professor of Chemistry
Washington and Lee University

February 2012

ACKNOWLEDGEMENTS

We are grateful to have had an all-star cast of experts to write the chapters. We chose them in order to show differing perspectives on the future of nuclear power in the United States. The views in the chapters are solely the authors and do not necessarily represent the views of the Federation of American Scientists or Washington and Lee University.

The report benefited from the copyediting and formatting of Monica Amarelo, FAS's Director of Communications. We are also thankful for the advice we received from numerous colleagues during earlier phases of our collaboration when Charles Ferguson worked at the Council on Foreign Relations.

We are very appreciative of the generous financial support from Mr. Harold "Gerry" Lenfest and the Lenfest Foundation and his dedication to educating the public about nuclear energy.

TABLE OF CONTENTS

About 4

Foreword 5

Acknowledgements 8

Chapter 1: Nuclear Power in the Global Energy Portfolio 10

Chapter 2: A Critical Examination of Nuclear Power's Costs 32

Chapter 3: Licensing and Regulation of U.S Nuclear Power Plants. 46

Chapter 4: Safety of Nuclear Power 57

Chapter 5: Security of U.S. Nuclear Power Plants 73

Chapter 6: Future Uranium Supplies for U.S. Nuclear Reactors 86

Chapter 7: Prospects for a Plutonium Economy in the United States 98

Chapter 8: Required Infrastructure for the Future of Nuclear Energy 108

Chapter 9: Alternatives to Nuclear Power 118

Chapter 10: Emerging Nuclear Technologies 128

About the Authors. 139

About the Editors. 143

Chapter 1

NUCLEAR POWER IN THE GLOBAL ENERGY PORTFOLIO

by Sharon Squassoni

Nuclear energy has generated commercial electricity for more than half a century. Although advocates had high hopes for its widespread use, nuclear energy growth in the last twenty years faltered on lower costs for alternatives like natural gas and a steep drop in public support after the reactor accidents at Three Mile Island and Chernobyl. In the United States, escalating costs and a nascent environmental movement halted virtually all new construction after 1978. Some countries, such as Japan, France and the Republic of Korea, however, embraced nuclear energy enthusiastically.

Today, nuclear power plants produce about 14 percent of global electricity. Without sustained and aggressive government support, this percentage is expected to decline to about 10 percent by 2030, according to the International Energy Agency. At least two factors will make it difficult for nuclear energy to gain a larger market share – overall electricity demand is projected to double, and older reactors will need to be retired.

It is this rising electricity demand, along with concerns about improving energy security and mitigating climate change that led many more countries to consider nuclear energy as a viable option. At least 27 nations since 2005 have declared they will install nuclear power for the first time and a total of 65 countries have expressed interest to the International Atomic Energy Agency (IAEA). This contrasts with the thirty countries plus Taiwan that are already operating nuclear power plants. The rganization for Economic Cooperation and Development's (OECD) Nuclear Energy Agency suggested in its 2008 Nuclear Energy Outlook that the world could be building 54 reactors per year in the coming decades to meet all these challenges.

For many reasons, an expansion of nuclear energy of this magnitude will be difficult to achieve. The current industrial base for nuclear reactors has supported just ten reactors coming on-line per year for the past two decades. The nuclear industry is scaling up its capacity but this could take some time. In some cases, the lack of a price on carbon dioxide emissions means that new nuclear power plant construction will remain relatively more expensive than coal, oil or natural gas, although this varies from country to country, depending on existing resources. Significant shale oil and shale gas discoveries have made utilities, at least in the United States, less enthusiastic about nuclear energy as a competitive source of electricity generation.

In response to mitigating climate change, many countries will find that nuclear power is neither the least-cost nor the quickest approach to reducing carbon dioxide emissions.1 Until nuclear energy is able to produce hydrogen or process heat, or until transportation sectors are electrified, nuclear energy's potential contribution to reducing carbon dioxide emissions will be somewhat limited.

Perhaps most importantly, the March 2011 accident at Japan's Fukushima Daiichi Nuclear Power Plant shook the confidence of the public not just in Japan but also abroad. The devastating earthquake and tsunami that killed tens of thousands of people eliminated off-site and backup electricity for four of six reactors and their spent fuel pools at Fukushima Daiichi. Hydrogen explosions destroyed secondary containments, exposing spent fuel pools, and three of the reactors had partial core meltdowns. The Japanese government evacuated some of the population immediately. The clean-up effort at Fukushima will drag on for years and the cost will likely range in the billions of dollars.

Other countries with operating nuclear power plants, including the United States, announced safety reviews, and some halted construction and even operation of existing power reactors.2 Several countries that had been considering nuclear power may face a significant challenge in overcoming public mistrust. Still, the long-term impact of the Fukushima accident on nuclear power in Japan and worldwide is unknowable. Although many countries regard the possibility of another event combining a magnitude 9.0 earthquake and tsunami to be very low, the difficulties Japan – a highly

---

[1] Energy Technology Perspectives 2008, International Energy Agency, (Paris: Organization for Economic Cooperation & Development) 2008, page 65. For example, in the Blue Map Scenario of the International Energy Agency's 2008 Energy Technology Perspectives, nuclear energy contributed to 6 percent of total CO2 emission reductions to 2050, despite an average build rate of 32 reactors per year. Other approaches contributed more to climate change mitigation: end-use fuel efficiency (24 percent); renewables (21 percent); end-use electricity efficiency (12 percent); end-use fuel switching (11 percent); carbon capture & storage (CCS) power generation (10 percent); CCS industry transformation (9 percent); power generation efficiency and fuel switching (7 percent).

[2] China temporarily halted construction; Germany shut down reactors pending a safety review; and Italy suspended a national referendum on nuclear power.

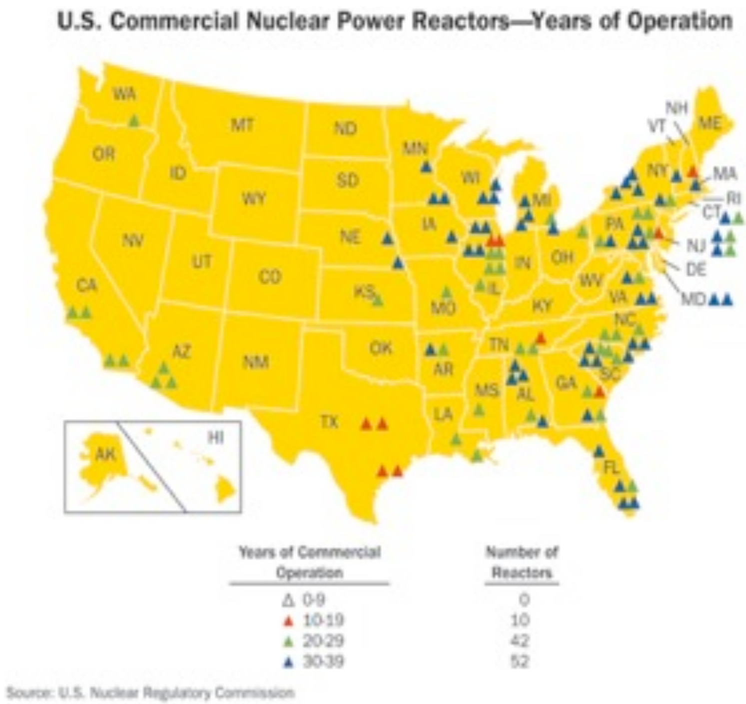
sophisticated and technologically competent country – experienced because of the lack of electricity is raising questions about the costs and risks of nuclear power.

Nuclear Energy in the United States: Promises of the Past

The 104 reactors operating in the United States constitute about 25 percent of world capacity. Commercial nuclear power in the United States was a direct spin-off from the military's nuclear programs. General Electric and Westinghouse leveraged their military nuclear contracts with the U.S. Navy and emerged as the two dominant reacto r vendors not just in the United States but in the world for many years. GE's introduction of the "turnkey" contract, which offered fully constructed power plants at a fixed rice, provided significant momentum to construction in the mid-1960s. Westinghouse followed suit to remain competitive. By 1967, American utilities had ordered more than 50 power reactors and in the next seven years, they placed an additional 196 orders.3 By 1973, 40 units were operating. These first- and second-generation reactors were built primarily by Westinghouse and GE, whose pressurized water (PWR) and boiling water (BWR) designs, respectively, were adopted worldwide. Two-thirds (69) of U.S. reactors are PWRs, and the remaining (35) are BWRs. Figure 1 shows the location of these plants.

[3] International Atomic Energy Agency , "50 Years of Nuclear Energy." General Conference 48 Document. Vienna, 2004. Available at www.iaea.org/About/Policy/GC/GC48/Documents/gc48inf-4_ftn3.pdf

Figure 1: Operating Nuclear Power Plants in the United States, 2011



Source: U.S Nuclear Regulatory Commission. Date: September 2008. Available online at http://www.nrc.gov/reactors/operating/power-reactors-map-sm.jpg

Along with construction of nuclear power plants, the Atomic Energy Commission (AEC) also encouraged spent fuel reprocessing and the development of plutonium breeder reactors, primarily in response to concerns about scarce uranium. In 1966, the AEC granted a license to Nuclear Fuel Services (NFS) to operate a commercial reprocessing plant at West Valley, New York, which reprocessed both defense-related material and commercial spent fuel until 1972. A temporary shutdown became permanent and NFS abandoned the plant to the State of New York. Legislation in 1980 committed the federal government to take on 90 percent of the cleanup costs, which have totaled $2 billion so far.

Two other reprocessing plants under construction never managed to operate: GE's Morris, Illinois plant, and Allied-General Nuclear Services' plant in Barnwell, South Carolina. Declared inoperable in 1974, the GE plant eventually stored spent fuel; the Barnwell plant was neither complete nor ready for licensing when the Carter Administration decided in 1977 no longer to support reprocessing and recycling, even domestically, because of proliferation concerns. By the time the Reagan administration reversed that decision in 1981, Allied-General decided the Barnwell project was commercially unviable.

Long before Three Mile Island, regulations on nuclear power in the United States began to tighten. In the early 1970s, critics of the AEC argued that its regulation was "insufficiently rigorous in several important areas, including radiation protection standards, reactor safety, plant siting, and environmental protection."[4] A 1974 reorganization of the AEC created the Energy Research and Development Administration (ERDA, now the Department of Energy) and the Nuclear Regulatory Commission (NRC). Creation of the Environmental Protection Agency, the Council on Environmental Quality and new requirements for environmental impact statements also had a significant impact, as did growing public interest in environmental issues. More than half the challenges to almost 100 construction permits for nuclear power plants between 1962 and 1971 came from environmentalists concerned about the impact of waste heat from power plants on the local waterways. The creation of the Critical Mass Energy Program (which reportedly had 200,000 members) by Public Citizen founder Ralph Nader in 1974 to lobby against nuclear power further increased the pressure.

The changed licensing environment began to affect new reactor orders by 1975. In the early licensing scheme, less than 50 percent of the engineering designs were generally completed before construction, requiring field engineering and backfitting based on operating experience in other plants.[5] These designs were released too early to engineering, procurement and construction. Slowdowns also came from utilities, because high finance costs and falling demand made it very difficult to borrow money to build plants no longer needed by the original dates. "Cost-plus" construction contracts also contributed to spiraling costs.[6]

---

[4] United States Nuclear Regulatory Commission, Our History. Washington, DC. 2009. Available at: http://www.nrc.gov/about-nrc/history.html.

[5] Hultman, Nathan E. and Jonathan G. Koomey (2007). "A reactor-level analysis of busbar costs for US nuclear plants, 1970-2005," Energy Policy. Volume 35, 2007, page 5638.

[6] Maloney, Steven, "Nuclear Construction Risk Drivers – Then and Now," presentation to Platt's Fifth Annual Nuclear Energy Conference, Bethesda, Maryland. February 13, 2009.

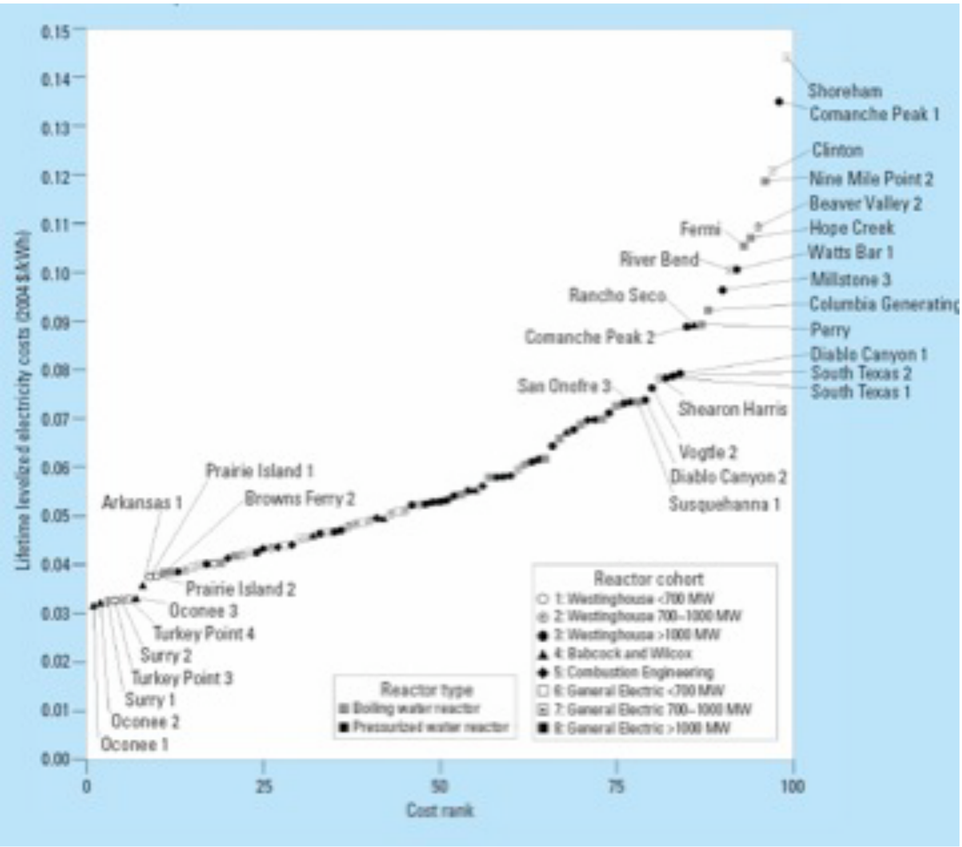
Cost overruns became more transparent and egregious, sometimes ten times above industry estimates. For the 75 reactors built between 1966 and 1977, cost overruns averaged 207 percent.[7] In the end, more than 100 reactor orders were cancelled, including all those ordered after 1973. Regulatory hurdles increased in the wake of Three Mile Island, which may partly account for even greater cost overruns for the 40 plants constructed after 1979, which averaged 250 percent.[8]

By 1985, popular magazines such as Fortune and Time had pronounced the death of nuclear power in the United States; Forbes magazine called it "the largest managerial disaster in history." The $2.25 billion municipal bond default of the Washington Public Power Supply System (WPPSS) plants in 1983 certainly contributed to that popular sentiment. The closing in 1989 of the Shoreham plant – fully constructed for $5.4 billion and never operated -- was the final nail in the coffin. The initial cost estimate for Shoreham had been $350 million.Figure 2 shows the distribution of costs (in 2004 dollars) for 99 U.S. reactors from 1970 to 2005, using a 6 percent discount rate.

---

[7] United States Congressional Budget Office,"Nuclear Energy's Role in Generating Electricity," May 2008, pp. 16-17.

[8] Ibid.



Source: Hultman, Nathan E., Jonathan G. Koomey and Kammen, Daniel M., "What History Can Teach Us About the Future Costs of U.S. Nuclear Power," Environmental Science and Technology, April 1,2007 p. 2,091.

Relaunching Nuclear Energy in the United States

Many of the Bush-era initiatives on nuclear power focused on new plant construction, but also on returning to a policy of promoting recycling of spent fuel. Although the Obama administration may have wished to avoid these debates altogether, its decision to cancel the Yucca Mountain repository in 2009 brought all these difficult issues to the fore as did the March 2011 accident at the Fukushima-Daiichi reactors, which especially highlighted safety concerns with spent nuclear fuel pools.

New Nuclear Power Plants

With the hiatus in building new plants, the nuclear industry has focused on improving operating efficiencies and refitting plants. The 1992 Energy Policy Act created a "onestep" licensing procedure for new nuclear reactors, combining construction and operation licenses, and limiting kinds of interventions but did not lead to any new license applications. Since 2000, however, a panoply of policies, laws, and programs to help jump-start new nuclear power plant construction has produced applications, if no real construction yet. A few of the highlights are listed below:

- 2001: the National Energy Policy Development Group recommends supporting "the expansion of nuclear energy in the United States as a major component of our national energy policy," including research and development for spent fuel recycling with the aim of reducing waste streams and enhancing proliferation resistance.

- 2002: Nuclear Power 2010 spends $550 million to help jump-start new power reactor construction. Includes shared costs with industry for regulatory approval of new reactor sites, applying for licenses and preparing detailed plant designs. Also includes development of early site permits separate from reactor design reviews to facilitate licensing process.

- 2001-2009: DOE R&D budget triples for nuclear energy. Programs included Generation IV program, the Nuclear Hydrogen Initiative Program (NHI), and the Advanced Fuel Cycle Initiative (AFCI).

- 2005: Energy Policy Act of 2005 includes incentives such as production tax credits, energy facility loan guarantees, cost-sharing, limited liability and delay insurance.

- 2010: Additional loan guarantees announced.

Of all these, the Energy Policy Act (EPACT) of 2005 and the issue of loan guarantees deserve more description. Under EPACT 2005, a production tax credit would provide 1.8 cents/kWh during the first eight years of operation of qualified new nuclear power plants. To put this in context, the average wholesale price of electricity in

2005 was 5 cents/kWh.9 The credit has a limit of $7.5 billion, or the first 6,000 MW of capacity (equivalent to about five plants). Only those projects that have applied for a combined construction-operating license by December 2008, and that begin construction by January 2014 and operation by 2021 are eligible for the credit.

The U.S. nuclear industry has singled out government loan guarantees as essential because the private market finds loans for nuclear power plants to be too risky, and U.S. utilities are too small to take on a bigger equity to debt ratio, which would lower the cost of capital, a key element in the cost of the new plants. Under the loan guarantee program, the U.S. Treasury will guarantee 100 percent of a loan which is limited to 80 percent of the construction costs. This effectively transfers the risk of cost overruns due to lengthier construction times from project owners to the taxpayer.

Congress appropriated $18.5 billion in loan guarantees for nuclear power facilities, and President Obama has recommended tripling this to $54 billion. This still falls far short of the $122 billion in requests. Industry sources suggest DOE will be able to support no more than 2-4 reactors, given costs of $5 billion to $12 billion per reactor. The Department of Energy awarded the first loan guarantee to the Vogtle reactor project in Georgia (over $8 billion) in 2010.

The DOE also committed to sharing design and licensing costs for the "first of a kind" reactor, with its share estimated at $281 million.10 EPACT also extended Price-Anderson limits on liability through 2025, capping new plants' liability in case of accidents at $10.6 billion. Finally, delay insurance would apply to the first six new licensed reactors delayed by the regulatory process; some $500 million would be available for each of the first two reactors and $250 million for each of the next four reactors. This was intended to compensate for delays in implementing the new combined construction and operating license process by the NRC.

Spent Fuel Recycling

As noted above, the Bush administration sought to close the nuclear fuel cycle in the United States by promoting the development of fast reactors to burn up plutonium and "recycling" waste for that purpose. The basic idea was to reduce the volume of nuclear

---

[9]United States Congressional Budget Office, "Nuclear Energy's Role in Generating Electricity," May 2008, p. 8. In December 2007 it was 8.9 cents/kWh.

[10] Ibid, page 10.

waste by reusing the fuel in fast reactors, which can burn more of the material. The Global Nuclear Energy Partnership (GNEP), the Advanced Fuel Cycle Initiative, and other related programs have all sought to implement that goal. Thus far, the U.S. Congress has taken a "go slow" approach, delaying demonstrations of advanced recycling technologies until more research can be completed.11 A National Academy of Sciences report in 2008, which reviewed DOE's nuclear energy R&D, suggested that DOE reconsider reactor technologies under the Gen IV program that would support both advanced fuel cycles and the production of process heat, instead of pursuing two reactor technologies – very high temperature reactors and sodium-cooled fast reactors – for those tasks. It also recommended that DOE continue research on advanced recycling techniques, rather than move toward a technology demonstration plant. The Obama administration has advocated research into a modified open fuel cycle in which some research would be conducted on conditioning spent fuel.

Current Status

The nuclear industry in the United States responded quickly to the incentives package provided in EPACT 2005. Three designs for pressurized water reactors and two boiling water reactor designs are now under consideration for this next round of nuclear power plants. These include Westinghouse's Advanced Passive Reactor (AP-1000), AREVA's European Pressurized Water Reactor (EPR); and Mitsubishi's Advanced Pressure Water Reactor (APWR). In addition, designs for GE/Hitachi/Toshiba's Advanced Boiling Water Reactor (ABWR) and GE/Hitachi's Economic Simplified Boiling Water Reactor (ESBWR) have also been submitted.

These are described in greater detail in later chapters. It should be noted that the hoped-for standardization of designs has not happened, that not all the reactors have yet been certified and that a few of these designs have submitted modifications to their applications. For example, the designs for both the AP-1000 and the ABWR have been certified by the NRC, but planned changes will require additional certification and in the case of the ABWR, design certification renewal. Only one project envisions building an ABWR. The design certification applications for the other reactors were

[11] United States Senate, "Global Nuclear Energy Partnership, Hearing Before The Committee On Energy And Natural Resources," First Session, To Receive Testimony On The Global Nuclear Energy Partnership As It Relates To U.S. Policy On Nuclear Fuel Management. Senate Hearing 110-306, 110th Congress, November 14, 2007.

submitted several years ago: the EPR and APWR in December 2007 and the ESBWR in 2005. The table below, adapted from Standard & Poor's, summarizes some of the differences among these technologies.

Table 2: Comparison of reactor designs currently under consideration in the United States

	Pressurized Water Reactors			Boiling Water Reactors	
	EPR	AP 1000	APWR	ABWR	ESBWR
Design certification status with NRC	Submitted Dec 2007	Modifications will require NRC certification	Submitted Dec 2007	Yes but modifications will require NRC certification	Submitted Aug 2005
Design (net) MWe	1,600	1,117	1,700	1,370	1,520
Capital costs	High	Low	Medium	Low	Low
Reactor coolant system	Four-loop	Two-loop	Four-loop	N.A.	N.A.
Active/passive safety systems	Active	Passive	Active	Active	Passive
Reactor coolant pumps (safety trains)	Four trains	Two trains	Four trains	Three trains	Two trains
O&M costs per kW	Medium	Medium	Medium	High	Low
Fuel efficiency	High	Medium	Medium	Low	High
Core damage frequency/year	5.8x 10 -7	5 x 10 -7	N.A.	1.6 x 10 -7	3 x 10 -7
Aircraft hazard protection	Yes	No	No	No	No
Construction track record	2 plants being built (Finland, France.) 2 in China soon to commence	None, but 2 in China soon to commence	None, but 2 in Japan soon to commence	4 Japanese units in operation, first since 1996	None
Modular construction?	No	Yes	Yes	Yes	Yes
Relative amount of steel and concrete	High	Low	Medium	Low	Low

Source: Swaminathan Venkataraman and Aneesh Prabhu of Standard & Poor's, "New Build Risks and the Nuclear Renaissance." At http://www.mhenergy.com/Magazines/Insight/2009/feb/2Hv009tC02031j20o651OF_1.xml

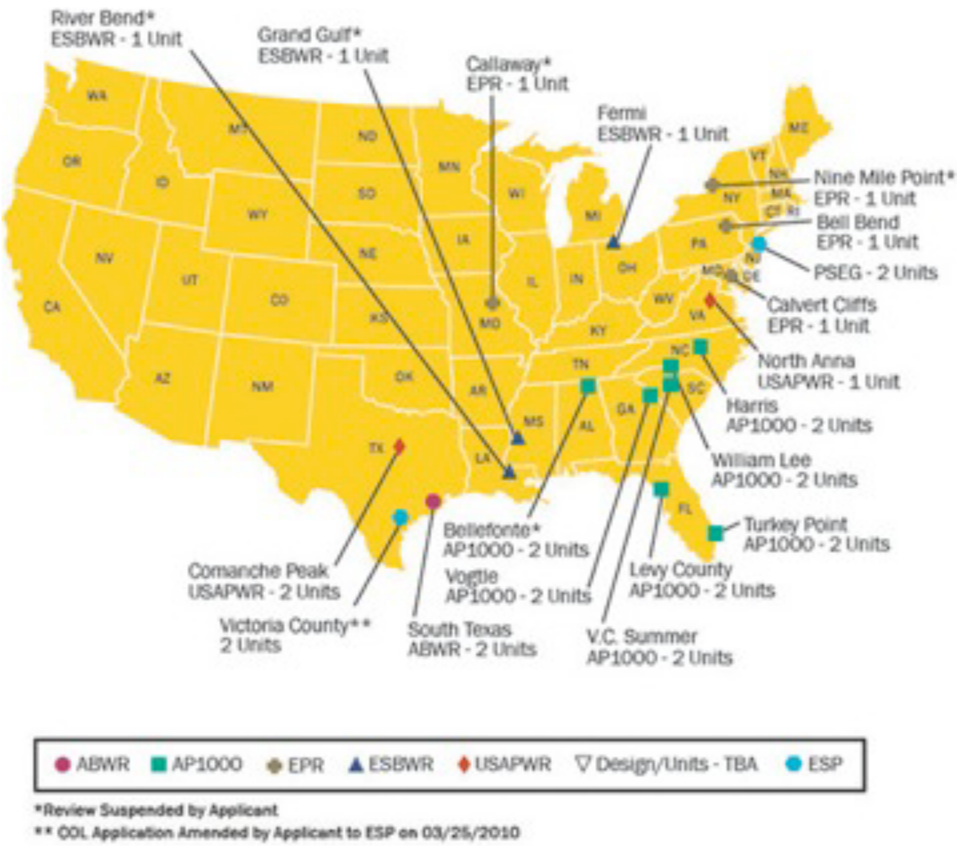
Four considerations affect the attractiveness of these designs for U.S. utilities: capital cost, time to market, evolutionary versus revolutionary technologies, and active versus passive safety design features. For the most part, unregulated electricity genera ors – such as Constellation Energy Group, NRG Energy Inc. and PPL Corp. – have chosen active safety designs, presumably because they rely on the market for cost recovery and therefore want the most proven technologies. Regulated utilities have so far valued the lower life-cycle costs of passive designs, choosing the AP-1000 and ESBWR. Although Exelon Corporation initially chose the ESBWR, it appears that in the wake of Fukushima, Exelon will focus on building natural gas plants as opposed to nuclear power plants, citing their overwhelming costs.

New License Applications for Nuclear Power Plants

As of December 2010, 17 licenses for constructing and operating 26 new reactors were filed with the NRC. By type of reactor, these include: fourteen AP-1000 (Westinghouse-Toshiba) at seven sites; three ESBWR (GE-Hitachi) at three sites; four EPR (AREVA) at four sites; two ABWR (GE-Hitachi) at a single site; and three APWR (Mitsubishi) at two sites.

Several of the license applications have been suspended by request of the proect managers, including Entergy for River Bend and Grand Gulf, and Exelon for Victoria County. NRG decided in April 2011 to terminate its involvement in the South Texas Project, and Constellation Energy decided in late 2010 to pull out of its deal with Electricite de France for the EPR project at Calvert Cliffs. EDF would like to go forward, but requires an American partner to do so. The map below shows the locations of sites for new COLs.

Figure 3: Location of Projected New Nuclear Reactors



Source: United States Nuclear Regulatory Commission, March 2011, available online.

Enrichment Plants

In the United States, four new enrichment plants are either under construction or awaiting licenses to begin construction. Until 15 years ago, the Department of Energy owned and operated gaseous diffusion uranium enrichment plants at Paducah, Ken ucky, and Portsmouth, Ohio. The 1992 Energy Policy Act privatized DOE's enrichment capabilities, creating the United States Enrichment Corporation (USEC). The remaining USEC plant at Paducah enriches uranium for domestic use and for export. U.S. utilities have relied on downblended Russian highly enriched uranium (HEU) for about half of their low-enriched uranium (LEU) fuel since 1995. The plant at Paducah, which is scheduled to shut down in the next few years (between 2010 and 2015), will be replaced by a six million separative work unit (SWU) capacity plant in New Mexico (the Louisiana Enrichment Site) and the Advanced Centrifuge Project, a gas centrifuge plant expected to produce about 3.8 million SWU per year using American technology. [12] The table below shows the new capabilities:

Table 3: Enrichment Projects in the United States

Consortium	Location	Technology	Capacity (SWU)	Date
AREVA	Eagle Rock, ID	gas centrifuge	3 million	2014-19
LES	NM	gas centrifuge	5.7 million	2009-15
USEC	Paducah, Kentucky	ACP	3.8 million	2010-12
GE-Hitachi	Wilmington, SC	AVLIS	3.5 million	2013-16

Source: Increasing Enrichment Capacity for a Growing Nuclear Industry; presentation by John M.A. Donelson, February 13, 2009

The Louisiana Enrichment Services (so called because Louisiana was the original proposed site) plant and the American Centrifuge Plant are licensed and under construction. LES decided to expand its enrichment capacity from 3 million SWU to 5.7 million SWU. USEC has been slow to finish construction on the ACP for several reasons. Its loan guarantee application was initially declined, but USEC submitted an updated version in August 2010 for $2 billion. The expected cost of going forward with the plant is at least $2.8 billion, not counting USEC's initial investment of $1.8 billion. Additional costs will include the costs of the loan guarantee, overall project contingency, financing costs and financial assurances.[13] USEC has also sought and received funding from Toshiba and Babcock and Wilcox for construction ($100 million each).

---

[12] Donelson, John M.A., "Increasing Enrichment Capacity for a Growing Nuclear Industry," Presentation to Fifth Annual Platt's Nuclear Energy Conference, Bethesda, Maryland, February 13, 2009.

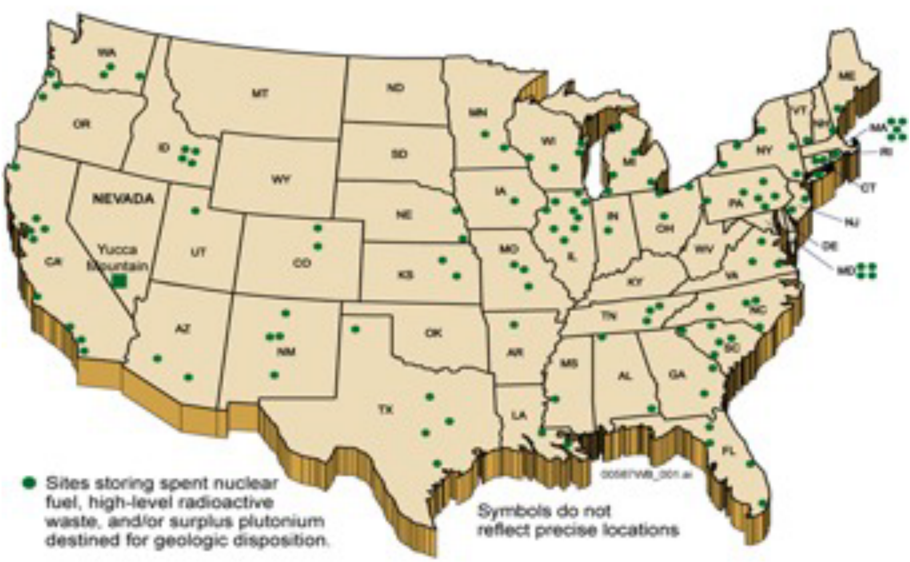
[13] See USEC's press statement on August 3, 2010, available at http://www.usec.com/NewsRoom/NewsReleases/USECInc/2010/2010-08-03-USEC-Submits-Update-To.htm

AREVA has applied for a license for a gas centrifuge plant at Eagle Rock and expects a decision in early 2012.

Waste Management

The history of nuclear waste management in the United States reflects a lot of studyand research, punctuated by a few decisions every few decades. In 1956, a National Academy of Sciences study group concluded that a deep geologic repository was the best solution to dispose of high-level waste from nuclear reactors. The Nuclear Waste Policy Act, however, was not passed until 1982. It appears now, almost thirty years later, that some parts of the law may need revision.

Figure 4: Location of Spent Nuclear Fuel



Source: Nuclear Regulatory Commission website. See ***http://www.nrc.gov/waste/spent-fuel-storage/locations.html***

Nuclear power reactors in the United States each year generate about 2,000 metric tons of fuel. So far, the United States has accumulated about 57,700 metric tons of spent fuel, which is stored in spent fuel ponds and in dry storage casks at 121 sites in 39 states. According to the 1982 Nuclear Waste Policy Act (NWPA), nuclear power plant operators are required to pay into the Nuclear Waste Fund (now estimated at $20 billion) in return for DOE waste disposal services – that is, eventual disposal in a geologic waste repository. That repository, designated as the Yucca Mountain site in 1987, was supposed to have opened in 1998. Beginning in 1997, nuclear power plant operators filed 56 lawsuits against the DOE for costs incurred in the absence of shipments to Yucca Mountain. DOE estimates that its liabilities under the current law will total $11 billion if shipments begin by 2020, and a lot more if they do not. The NWPA did not provide for another method of disposing waste, such as reprocessing, and the Nuclear Waste Fund may not be used for anything other than legislated purposes. Further delays are ahead, since the Obama administration decided to cancel construction funds for the Yucca Mountain program in early 2009, while continuing the licensing process at the NRC. This raises the question of whether the funding decision could be reversed in the future. If so, advocates of Yucca Mountain would still need to address storage capacity and geology issues. The NWPA set an arbitrary limit of 70,000 tons for Yucca Mountain, but it presupposed a second waste site would be authorized. By 2020, the level of waste is expected to reach 81,000 metric tons. Including defense waste and shipments by U.S. reactors through 2066, the expected accumulated waste is estimated to reach 122,100 metric tons.[14] Geologic issues include the risk of transporting radioactive wastes in a porous environment, because fractures in volcanic tuff can transport water, and the location of the Bow Ridge fault line underneath a facility, rather than a few hundred feet away.

Public Debate

Nuclear energy had not been debated seriously in the United States for decades until the Fukushima accident. Support for nuclear energy in the past ten years has focused on concerns about rising energy prices and dependence on foreign sources of energy. For example, a February 2008 Pew on-line survey indicated that a majority of Americans believe "developing new sources of energy, rather than protecting the

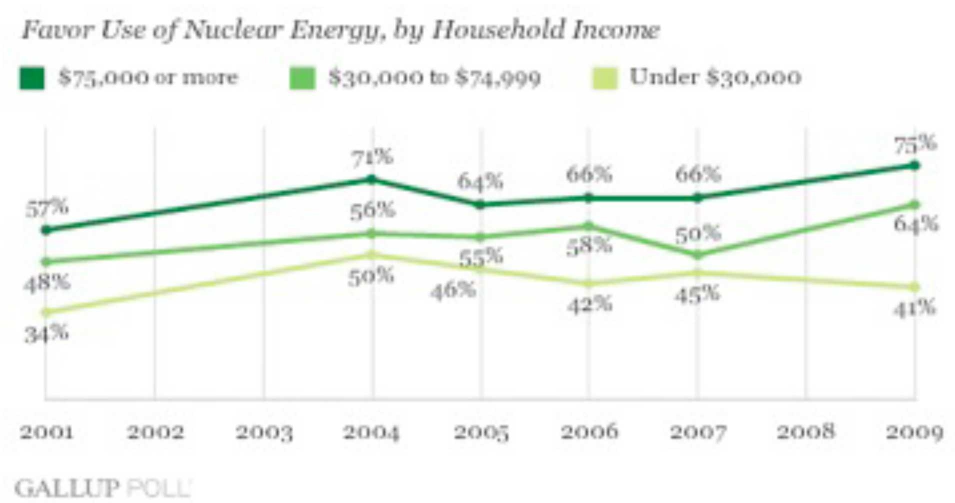
---

[14] Holt, Mark, "Nuclear Waste Disposal: Alternatives to Yucca Mountain," Congressional Research Service Report, R40202, February 6, 2009.

environment, is the more important priority for the country (Pew, 2008)." The Pew survey reported 48 percent of Americans opposed promoting more nuclear power, while 44 percent favored doing so. This contrasts with a 2008 UPI/Zogby International Poll showing 67 percent support for nuclear power, and 23 percent opposed to building new nuclear power plants.[15]

Gallup polls in the last decade shown in Figure 5 below reveal a steady increase in favorable support for nuclear energy and a steady decline in negative numbers until Fukushima. The progression began in 2001 at 46 percent favoring nuclear power and 48 percent opposing nuclear power and climbed to 62 percent favoring nuclear power in 2010 and 33 percent opposing the use of nuclear power.

Figure 5: Gallup poll on nuclear energy for electricity in the United States, March 2009



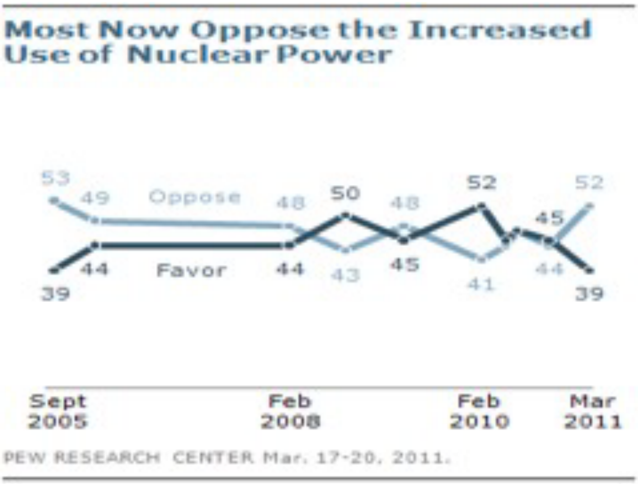
Source: Gallup poll, March 20, 2009, available at
http://www.gallup.com/poll/117025/support-nuclear-energy-inches-new-high.aspx

Concerns about contamination of the soil and water by radioactivity lay relatively dormant in recent years because of the strong support of the U.S. government for

15 See poll cited at
http://zogby.com/news/2008/06/06/zogby-poll-67-favor-building-new-nuclear-power-plants-in-us/

nuclear power and the portrayal of nuclear energy as "clean, green and secure." Marketing campaigns by the Nuclear Energy Institute (NEI) portraying nuclear energy as "clean air" energy and by the NEI-funded the Clean and Safe Energy Coalition were likely influential.[16] On the whole, opponents of nuclear energy generally have had less money to spend on media campaigns, and their message is less pithy. They have stressed that nuclear power is not the solution to climate change and that it is dangerous, polluting, unsafe, and expensive. The accident at Fukushima returned safety and waste concerns to headline news. Shortly after the accident, a Gallup poll showed 44 percent of the public in favor (in contrast to 59 percent the previous year) and 47 percent opposing nuclear power.[17] Figure 6 below shows the results of a Pew Research Center poll conducted about a week after Fukushima.[18]

Figure 6: Pew Research Center Poll on Nuclear Power, March 2011



[16] CASEnergy Coalition apparently supports nuclear energy as the only form of clean and safe energy. It is co-run by former EPA Administrator Christine Todd Whitman and former Greenpeace activist Patrick Moore.

[17] See http://www.gallup.com/poll/146660/Disaster-Japan-Raises-Nuclear-Concerns.aspx

[18] Available at http://people-press.org/2011/03/21/opposition-to-nuclear-power-rises-amid-japanese-crisis/

Many polls differentiate between support for existing nuclear power plants versus expansion. Often, there is public support for the continued operation of plants but perhaps less support for new plants, especially on new sites. Fukushima raised concerns about existing U.S. reactors, particularly those of the same design as the Japanese reactors (of which there are 23 in the United States). President Obama called for a 6-month review by the Nuclear Regulatory Commission of the safety of U.S. reactors and Congress held several hearings in March and April 2011.

Whether Fukushima will have a lasting negative impact on public opinion in the United States about nuclear energy is unknowable. Much depends on what happens in Japan, both in terms of cost and environmental consequences, and what happens in other countries such as Germany, Switzerland, and the UK. Public opinion will also be swayed by the strength of U.S. government support for nuclear power as a component of clean energy. While loan guarantees will undoubtedly continue, the enthusiasm of the Obama Administration could diminish.

Outlook for the Future

Regardless of public opinion, the outlook for nuclear energy in the United States will be at best, slow progress, possibly bolstered by success in managing and executing the first five reactors. Lower natural gas prices threaten to derail the current interest in nuclear power by U.S. utilities, and loan guarantees, while necessary, are not sufficient. effrey Immelt of General Electric suggested a few years ago that only "five to ten U.S. nuclear power projects would go ahead unless there was a carbon-pricing framework to create incentives for utilities to build more."19 John Rowe of Exelon stated his own preference for building other electricity generation plants in an interview with Bloomberg news on March 16, 2011.20 For both, building other electricity-generating plants would continue to be more cost-effective than new nuclear power plants.

A carbon "tax" would need to be higher than $30/ton of carbon dioxide and

---

19 Crooks, Ed and Francesco Guerrera (2007). "GE chief urges incentives to fuel nuclear switch," Financial Times. November 18. Available at
http://us.ft.com/ftgateway/superpage.ft?news_id=fto111820071727554141&pag=1

20 See http://www.bloomberg.com/video/67720906/

possibly as high as $100/ton.[21] Yet prices in carbon trading in Europe in the first three years varied from about €30/mt to less than €0.02/mt; in the second round of trading, allowances have been hovering in the low €20/mt (equivalent to $50/mt) range.[22] In the first half of 2009, the price hovered at 13 Euros/mt. A stable, long-term price for carbon is far from assured.

A climate bill in the Congress has been stalled in the Senate for more than a year, even though the House managed to pass a bill in June 2009 (American Clean Energy and Security Act). Although some progress is achievable in the energy appropriate ions bills, a carbon price is widely believed to be politically too difficult, particularly with a Republican-dominated House of Representatives that does not consider climate change as an urgent issue. That said, coal and natural gas will continue to provide the bulk of electricity generation in the United States. With abundant supplies (particularly arly now with the development of shale natural gas) and lower facility construction costs, both are cost-effective, particularly in deregulated markets. Some restrictions may occur at the state levels. For example, in February 2009, Michigan Governor Jennifer Granholm called for a near moratorium on new coal-fired power plants, which would affect eight new coal plants now in the approval process.[23] In Florida, concerns about dependence on natural gas and the ability to pass on construction costs to ratepayers have led to continued focus on nuclear power, despite high cost estimates.[24]

A wildcard in the mix may turn out to be recommendations from the Blue Ribbon Commission on America's Nuclear Future, which are scheduled to be provided to the President and Congress in late 2011 or early 2012. Secretary of Energy Chu appointed

---

21 Williams, Robert, "Can We Afford to Delay Rapid Nuclear Expansion Until the World is Safe for It?" Presentation to Bulletin of Atomic Scientists Future of Nuclear Energy Conference. Chicago, Illinois. November 1-2, 2006. Available at: http://www.ipfmlibrary.org/wil06.pdf. See also Massachusetts Institute of Technology (MIT), єe Future of Nuclear Power: An Interdisciplinary MIT Study. Cambridge: MIT, 2003.

22 Ryan, Margaret, "Platt's White Paper: Profitable Operations and Carbon Costs are Key to Nuclear Power Enthusiasm," (NY: McGraw-Hill Publications) May 2008, page 3.

23 Hornbeck, Mark; Charlie Cain; and Gary Heinlein, "Governor pushes greenpower," Detroit News. February 4, 2009. Available at http://www.detnews.com/apps/pbcs.dll/article?AID=/20090204/POLITICS/90200388/1026.

24 Jeffrey Lyash of Progress Energy Florida has predicted that Florida will depend on natural gas for 55 percent of its electricity generation by 2017. Florida has built only natural gas plants since 1984, which are not considered to be optimal baseload electricity generators because their fuel costs fluctuate significantly.

the Commission in early 2010 at the request of President Obama. The Commission, hich is co-chaired by Lee Hamilton and Brent Scowcroft, was tasked to "conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense sed nuclear fuel and nuclear waste. This review should include an evaluation of advanced fuel cycle technologies that would optimize energy recovery, resource utilization, nd the minimization of materials derived from nuclear activities in a manner consistent with U.S. nonproliferation goals.25 Perhaps to influence the Commission or to oreshadow its decisions since several Commission members were involved with the tudy, the Massachusetts Institute of Technology made its own recommendations from its study on the Future of the Nuclear Fuel Cycle in September 2010. The study recommended, among other things, that the United States should:[26]

- Accelerate the incentives provided to "first movers" – the first 7 to 10 new plants to make the costs of electricity from new nuclear power plants competitive with that of coal.

- Continue the once-through fuel cycle with light water reactors, focusing on improved fuel utilization.

- Use centralized storage for spent fuel for up to 100 years.

- Establish a new nuclear waste management organization that is quasigovernment.

- Integrate waste management with design of fuel cycles and pursue vigorous R&D for innovative reactors and fuel cycle approaches; and

- Pursue fuel-leasing options for nonproliferation purposes.

---

25 The members of the commission span a range of backgrounds, and include Mark Ayers of the AFL-CIO; Vicky Bailey, former DOE Assistant Secretary; Professor Albert Carnesale; former Senator Pete V. Domenici; Susan Eisenhower; Inc.; former Senator Chuck Hagel; Jonathan Lash, President, World Resources Institute ; Professor Allison Macfarlane; Richard A. Meserve, former Chairman of the NRC; Professor Ernie Moniz; Professor Per Peterson; John Rowe, CEO of Exelon Corporation; and Phil Sharp of Resources for the Future.

26 See http://web.mit.edu/mitei/research/studies/nuclear-fuel-cycle.shtml for the text of the full report.The summary report was released in September 2010 and the full report completed in March 2011.

The MIT study highlighted one of the biggest issues for nuclear power in the United States – its lack of cost-competitiveness with other means of electricity generation. It is unlikely, however, that accelerating the current incentives for nuclear power plants will be enough to motivate significant nuclear power plant construction in the United States. What is needed is a price on CO2 emissions, which is infinitely more difficult for the executive branch to engineer.

In the end, U.S. nuclear energy growth can only be achieved with a combination of aggressive government support and a complete revamping of the U.S. nuclear industry to stress standardization and modularization in construction. Foreign capital is also likely required. Even then, the challenges are formidable: just to maintain its share of the electricity market, the nuclear industry would need to build 50 reactors in the next 20 years. The best approach for the U.S. nuclear industry over the next five years will be to demonstrate that it can manage each stage of the licensing, construction and operating processes of the first four reactors competently and efficiently. In short, U.S. nuclear energy needs to prove it has overcome the problems of the past.

Chapter 2

A CRITICAL EXAMINATION OF NUCLEAR POWER'S COSTS

by Stephen Maloney

Since the nuclear industry's inception more than 50 years ago, its forecasts for costs have been consistently unreliable. The "first generation" plants, comprising both prototype reactors and the standard designs of the 1950s-1960s, failed to live up to promised economics. This trend continued with the construction of Generation II plants completed in the 1970s, which make up the present nuclear fleet.

First, the total costs were far higher than for coal-generated electricity. In particular, the capital cost of nuclear plants built through 1980 were, on average, 50 percent higher than comparably-sized coal-fired plants, adjusting for inflation and including backfits to meet Clean Air Act standards. Second, there were extraordinary cost escalations over the original low cost promises. Nuclear plant construction costs escalated approximately 24 percent per calendar year compared to 6 percent annual escalation for coal plants. Third, the economies of scale expected were not achieved in the Generation II designs. The scale-up of nuclear plants brought less than half the economic efficiencies projected.

In addition, over 120 nuclear units, approximately half the reactors ordered, were never started or cancelled. The total write-offs were more than $15 billion in nominal dollars. The red ink hit vendors and utilities alike, and cut across geographies, company structure, company size, reactor design, and experience.

In the late 1970s, the Atomic Industrial Forum (AIF), predecessor to the Nuclear Energy Institute, identified the main drivers of unmet expectations as growing understanding of nuclear accident hazards, failure of regulatory standardization policies, and increased documentation standards to ensure as-built plants actually met safety standards. The combined effects doubled the quantities of materials, equipment, and labor needed, and tripled the magnitude of the engineering effort for building a nuclear power plant. In effect, AIF explained the failure of the cost forecasts in terms of trying to hit a continuously moving target.

But the AIF assessment suggests that policy changes could make the cost target easier to hit. That may not be the case. Unlike other generating technologies, nuclear construction is inherently more complex; complex technologies are prone to cost underestimation. In addition, project dynamics can be significant. The cost of materials was assumed to be predictable when, in fact, they were subject to unprecedented monetary dynamics in the post-Vietnam War era. The cost of capital was assumed to be low when, in fact, it would rise through the 1970s to extraordinary levels in response to Federal Reserve Bank policy initiatives to combat asset deflation. Moreover, utility balance sheets were assumed to be "bankable" when, in fact, severe liquidity and capital constraints were adversely affecting the utility sector by the late 1960s limiting its ability to add high-cost capacity power plants in a recessionary market. Furthermore, the demand for power was expected to grow at a premium to sustained GDP growth when, in fact, demand stalled following the 1973 oil embargo, the step-change increase in energy prices, and the subsequent recession and deflationary periods.

Nuclear Construction Overruns before the General Design Criteria

Nuclear construction projects have always over-run their original estimates. The first generation of U.S. nuclear power plants (pre-General Design Criteria plant (1954 to about 1967)), and Generation II plants subject to "standardized" requirements of the General Design Criteria (GDC)) both experienced similar overruns.[1]

Consider, for example, Consolidated Edison Company's Indian Point Unit 1. Announced in October 1954, and built before the Atomic Energy Commission's (AEC's) Regulatory Staff published nuclear licensing and safety design criteria, the forecasted cost for this thorium-fueled 275 megawatt (MWe) breeder reactor was $55 million. It entered service in 1962 at $110 million. Other prototypical plants experienced similar overruns.

Vendors attempted to achieve economies of scale and scope through larger plants and standardized designs. For example, the Oyster Creek plant announced in December 1963 was nearly twice as large as Indian Point 1, and was the first of the so-called "turnkey projects" – plants designed and built to specifications. Most turnkey

[1] See: "General Design Criteria for Nuclear Power Plant Construction Permits," 10 CFR Part 50, July 11, 1967, http://pbadupws.nrc.gov/docs/ML0433/ML043310029.pdf

plants entered service between late 1969 and 1972. Reportedly, Oyster Creek was the single largest "loss leader" among such projects. By 1966 when the turnkey sales program ended, General Electric and Westinghouse were reported to have taken nearly $1 billion in losses constructing the 13 reactors in this class.[2]

Standardizing Nuclear Regulation: the GDC and its Defects

Regulatory standardization is rooted in risk analysis. As knowledge of nuclear technology evolved, the hazards became better understood. But plants are built to standards defined in the past. Costs rose as the "as-built" plants were modified to meet the growing awareness of the hazards.

The 1954 revision to the Atomic Energy Act included instructions to the AEC to issue licenses to private companies to build and operate commercial nuclear power plants, as well as possess fissionable material. To be effective, safety standards needed to relate to the hazard of a reactor accident. The AEC tasked Brookhaven National Laboratory to quantify the risk of a reactor accident. This study, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants" (WASH-740), was published in March 1957, and set the stage for the definition and evolution of reactor licensing and safety requirements.

WASH-740 analyzed a so-called "worst case" reactor accident scenario at a hypothetical 185 MWe reactor located some 35 miles from a major city. The analysis made a number of assumptions for core damage dynamics and airborne dispersal of fission products. WASH-740's hazard findings were stunning: a worst-case accident could result in 3,400 deaths, 43,000 injuries, and several billion dollars in property damage. AEC embarked on a research program to better understand reactor safety, and standardize and strengthen safety standards applied to plants under construction. This process often led to backfits.

A detailed summary report of then-current emergency core cooling (ECCS) technology was published in early 1971 as the "Brockett Report" and highlighted design inadequacies in a design basis accident. Most backfits were systemic in nature and the "knock-on" effects rippled through plant designs. For example, ECCS upgrades meant more water would have to be injected sooner in an accident and at higher

---

[2] H. Stuart Burness, W. David Montgomery, and James P. Quirk, "The Turnkey Era in Nuclear Power," *Land Economics*, Vol. 50, No. 2, May 1980.

pressure requiring larger pumps and valves. Larger pumps would lead to larger pipes, larger pump motors to drive the pumps, and larger emergency diesels to power these larger loads. Redesign imposed delays and inefficiencies in the construction process.

At the time, 53 plants were well along in their construction. The redesign of the ECCS capabilities during mid-construction triggered ripple effects of detailed engineering, procurement, design, and construction requirements over the next 10 years. These affected equipment qualification to perform under accident conditions, seismic protection, pipe rupture in reactor accidents, risk of heavy loads damaging structures, systems, and components important to reactor safety, flood protection, tornado protection, fire protection, structural integrity of concrete, reactor containment penetration integrity, and electrical system independence and protection.

Quality assurance (QA) standards were also introduced into safety regulations amidst the design and construction boom. Backfitting this program had an especially significant effect on construction costs. The original QA requirements were contained in a 1967 policy statement. In 1970, this general statement was amplified with the publication of Appendix B to 10 CFR 50. At the same time, the American National Standards Institute (ANSI), the parent standards body, organized committees within its member professional societies to develop detailed standards for meeting the new criteria. Twenty-four new quality assurance standards were published amidst the peak construction period of the 1970s.

Assimilating QA requirements into ongoing engineering and construction processes, however, was not always easy. An extreme example of QA problems is evident in the Zimmer plant. Some 10 years after publication of 10 CFR Part 50 Appendix B and as the plant was nearing completion, Nuclear Regulatory Commission inspectors cited the plant for problems in its QA program. These defects surfaced in a growing number of pipe weld inspections. Tracing the defects to engineering and design processes, NRC staff found other process deficiencies and eventually concluded the defects implicated the processes used to procure the plant's components and contractors. The more NRC looked, the more systemic the quality concerns became. As the number of deficiencies grew, the more the inspectors looked. By late 1982, the deficiency and corrective action lists reached a point whereby NRC issued a stop-work order on the project so everyone could get a handle on things. By then, the cost estimates to complete the project had grown to $3.4 billion. The owners cancelled the project in 1983. The original cost estimate for Zimmer was $230 million.When cancelled, the plant's sunk costs were said to total about $1.8 billion, almost equal to the owner's net worth. To salvage some value from the project, Zimmer was converted into a natural gas-fired facility.

Economic Considerations

The evolution of reactor designs and regulations undermined the reliability of the original nuclear cost projections. The construction risk was further amplified by economic conditions that slowed the demand for electrical power, increased commodity costs, weakened utility balance sheets, and raised the cost of capital. Many first and second generation plants were cancelled when it became evident that the total debt for the plant would approach the owners' book value (e.g., Zimmer). In other cases where a utility's capital adequacy was sufficient to complete a construction project, capital markets were often not deep enough to fund the risk.

It is often forgotten just how poorly positioned utilities were to take on the risk of building nuclear power plants. Entering the 1970s, the capital adequacy at electric utilities was well into decline with balance sheets marked by general illiquidity. Beginning in 1966, current liabilities at utilities exceeded current assets. By 1974, in the aftermath of the oil embargo, the combination of weaker earnings performance and continued heavy bond financing drove up the spread or "risk premium" on interest rates paid by electric utilities compared to industrial firms in the same bond-rating category. By 1975, power demand had dropped as electric rates rose due to higher fuel costs. With sector profits down some 25 percent and excess generating capacity in the system, utilities began to trim capital spending centered on the more expensive nuclear construction programs. By 1979, the credit window for nuclear plants had effectively closed. Lenders were increasingly cautious about financing utilities.

To summarize, forecasts for the first generation and second generation of nuclear plants were systemically wrong. But even if they were right, economic conditions had changed for many companies. The demand curve shifted. Cost of capital increased. By 1975, most utilities lacked the balance sheet needed to build a licensable plant.

Thirty years later, with this experience in mind, it is reasonable to ask what, if anything, has really changed:

- Are utilities better able to forecast and manage costs?
- Do they have the balance sheet to shoulder that risk?
- If not, who should bear the risk?
- Do the many billions of dollars of federal loan guarantees make sense from a taxpayer perspective?
- Would taxpayers be better protected with credit deposit fees? How much should those fees be?
- What price on carbon emissions would help even the playing field for nuclear power plants?
- What financing models are effective? Is the United States going about financing nuclear power plants the wrong way? How can it do a better job?

Will Future Nuclear Power Plants Follow a Similar Cost Trajectory?

The First and Second Generation nuclear plants teach the importance of regulatory stability. However, regulatory stability alone is not sufficient for reliable cost estimates. While today the reforms of combined construction and operating license (COL) application and preapproved design certification are expected to dampen cost escalations, safety regulations are not static nor can they be. The reformed process is not all encompassing as some might think. For example, NRC's design pre-approvals only apply to engineering documents submitted for review. But most design details are not presented for such review (e.g., detailed design and field engineering).

Indeed, substantial questions continue to be raised concerning one or another element of certified designs. The original Design Certification rule approving the Westinghouse AP1000 design was issued on January 27, 2006. Yet, substantial design details were not presented for NRC review at that time. According to the NRC, the largest review effort centers on the expected design changes required to address site features and other design changes identified after certification. Those design changes are substantial and include a redesign of the pressurizer, a revision to the seismic analysis to allow an AP1000 reactor to be constructed on site with rock and soil conditions other than the hard rock conditions certified in the AP1000 design certification review (DCR), changes to the instrumentation and control (I&C) systems, a redesign of the fuel racks, and a revision of the reactor fuel design. Another area requiring attention will be the review of design acceptance criteria (DAC)-related items, such as the technical reports on human factors engineering (HFE), the I&C design, and piping.

About a year later, the vendor submitted an application to amend the AP1000's DCR and Revision 16 of the AP1000's design certification design. Revision 16 contains changes proposed in technical reports, some of which have not yet been reviewed by the NRC staff. By February 2008, two years following certification, Westinghouse submitted 122 technical reports for NRC review. Although submitted as part of the Bellefonte Nuclear Power Plant's COL pre-application phase, these technical reports apply generically to the remaining COL applications that intend to reference the AP1000 design. Six months later, additional changes were submitted. Design Certification does not eliminate the need for detailed engineering design review, nor does it preclude design revisions.

Learning Curve in Engineering and Construction

Despite reconstituting the regulatory process, nuclear technology is no less complex today. While a stable regulatory process may reduce the potential for rework caused by changing requirements, it does not reduce the complexity of power plant design and construction. Also, regulatory stability does not equip companies with experience in planning and building a plant. As with previous generations, companies building a nuclear power plant today have no contemporaneous experience. Every plant built will be a "first-time" and an entirely new learning curve for each individual and organization. That learning curve applies as much to estimating commodity prices, quantities, and schedule as it does to forecasting the processes associated with procurement and construction.

Although there is no evidence of improvements in cost estimation, there is contemporary evidence of rising cost estimates similar to what happened in the first generation. Nuclear vendors in the early 2000s were quoting nuclear electricity generation's costs below $1,500/kWe. Within a few years, a utility consortium building a General Electric advanced reactor design priced two units at $1,611/kWe. A Florida company subsequently estimated a two-unit Westinghouse project would come in at $2,444-$3,852/kWe. The utility reported costs for materials, equipment, and labor had risen more than 50 percent. For all-in costs (i.e., transmission improvements, site enhancements, land, and risk) the project climbs to $3,108-$4,540/kWe. The company then dialed in 11 percent carrying charge and cost escalation allowances for a final tally of $5,780-$8,071/kWe.

The CPS Energy project history is also instructive. In June 2006, a consortium of companies announced plans to build two more reactors at the South Texas Project site for an estimated cost of $5.2 billion. NRG, the lead company, made history by becoming the first company to file an application with the NRC. CPS Energy, a municipal utility, was one of its partners. In October 2007, CPS Energy's board approved $206 million for preliminary design and engineering. In June 2009, NRG revised the estimate to $10 billion for the two reactors, including finance charges. A few weeks later, this estimate rose to $13 billion, including finance charges. Later that year, the estimate reached $18.2 billion, which was reportedly at the break-even point with natural gas, and the power would not be needed until about 2023. Whereas the reactors would require upwards of 10 years to build, price-competitive natural gas could be on-line in three to five years. CPS would reportedly spend about $1 million per day on the nuclear project, which would not be needed for some 20 years. Moody's had downgraded CPS's outlook to negative. When the municipal exited the project, its credit rating was lifted to stable.

This cost experience is not unique to the United States. Faced with stringent greenhouse gas (GHG) emissions standards under the Kyoto Protocol, Finland committed in 2004 to building Olkiluoto, the first Generation-III+ reactor, to enter production in 2009. Areva, based in France, won the contract to build the first Evolutionary/European Pressurized Water Reactor (EPR). At $3,000/kWe (2004), the plant was considered a "loss leader," similar to the "turnkey plants" of the 1960s. By 2007, project costs escalated 50 percent and construction schedule delayed three years. Construction cost projections doubled by 2008 mostly due to commodity cost escalations and weakening dollar to euro exchange rates in the intervening period. At the time, the plant was over $2 billion over budget.

As the project proceeded, quality assurance issues began to emerge. For example, late 2008, the Finnish Nuclear Safety Authority (STUK) questioned the supervision and "safety culture." STUK reported mandatory welding guidelines were not developed until months after welding of the reactor began and that a contractor instructed workers not to report quality problems to inspectors. Other QA concerns implicated the steel liner of the Olkiluoto reactor containment, and the remanufactured primary coolant piping.

Quality assurance deficiencies contributed to pushing back the delivery scheduled for the fourth time in two years out to 2012. In mid-2009, the latest estimate of construction costs reached EUR5.5 billion, more than twice the price of EUR 2.5 billion originally presented. By the end of 2009, more weld faults led to STUK issuing a "stop work" order until the issue is resolved. In mid-June 2010, Areva set aside some EUR400 million ($491 million) for the Olkiluoto 3 construction project leading to an operating loss for the first half of 2010.

In Canada, the Ontario government suspended its nuclear development project in mid-2009 when project bids came in around $C26 billion, some three times higher than what the province expected to pay. In 2007, the Ontario Power Authority assumed nuclear project costs of $C2,900/kWe installed. The Power Authority had quoted a break-even with natural gas of around $C3,600/kWe installed. The $C26 billion price tag would have constructed two 1,200-megawatt Advanced CANDU reactors (~$C10,800/kWe installed). Analysts have attributed the cost increases to labor, commodity, and vendor risk premiums.

Who bears the risk going forward, and who should bear it?

Risk is traditionally borne by those who benefit from the investment. With major capital projects, that risk is assumed by those holding the securities and is priced into credit availability and capital cost for the financial structure employed.

Construction Risk and Evolving Project Finance Structures

Construction risk manifests itself in two ways: (1) uneconomic construction costs that cannot be recovered, and (2) credit events associated with a range of scenarios from technical default through bankruptcy. For the first and second generation plants, ratebase disallowances often led to claims against the vendor. When construction projects overrun, both parties are often damaged. Both parties were at risk.

The first generation and second generation plants were funded by mortgage bonds financed by utility balance sheets and paid for by ratepayers. As the cost of capital through the 1970s rose, ratepayers paid the price of the flawed cost estimates.

Today, while the cost of capital is lower at the moment, credit availability is constrained by other market effects, notably persistent under-performing assets, a weakened banking system, and rising sovereign risk issues. Recognizing the limitations of today's credit markets, some companies would like to follow this model. The problem is that ratepayers are more likely to be resistant. Balance sheets for utilities are less able to handle the much larger construction risk of today's nuclear units.

The Nuclear Energy Institute argues that electric power companies are too small to generate the financing capability or strength needed to finance nuclear power projects on their own. NEI considers it essential that project partners (e.g., nuclear vendors) and limited investment incentives provide the necessary backup to otherwise limited balance sheets. The federal loan guarantee program helps serve this purpose. Power projects today often use limited or non-recourse financing through a vehicle company (separately incorporated) whose sole purpose is to bring assets online. Creditors share a portion of the venture's business risk and capital funding is obtained strictly for the project itself. In a non-recourse finance model, there is little expectation that the corporate or government sponsor will fully guarantee the debt. The vehicle company's equity might be entirely held by the parent utility. In other cases, equity might be distributed among several companies in an attempt to diversify risk as well as take advantage of some unique elements of the partners. A nuclear vendor might participate to further share risk. To help with local interests and municipal preferences in some jurisdictions, a municipal or power cooperative might be invited to a minority position. The problem is that few lenders will be willing to provide non-recourse financing because their balance sheets are not much stronger than their utility partners.

Securitization is one approach for diversifying the risk and has been advocated by some investors in recent years. Like the collateralized debt obligations, securitization combines contractual debts and sells the debt as a bond or security. In the utility sector, securitizations were originally used to address stranded costs following deregulation. It has also been used to reimburse utilities for storm restoration costs following two active hurricane seasons in the U.S. in 2004 and 2005. However, securitization rates are down today, a victim of failed risk management policies associated with collateralized debt obligations that led to the collapse of Bear Stearns and Lehman Brothers.

The bottom line is that, without back-end guarantees, even the most innovative structures and risk sharing among participants are challenged by the weak balance sheets of utilities and vendors alike. That leaves the government as an essential player in any nuclear renaissance.

Do the many billions of federal loan guarantees make sense from a taxpayer perspective?

On February 16, 2010, $8.3 billion in federal loan guarantees were awarded for two new reactors to be added to Southern Company's Vogtle site in Georgia, conditional until the project is awarded a combined construction and operating license from the NRC.

The DOE budget proposal for 2011 requested $36 billion in such loan guarantees, up from the current authority of $18.5 billion, with the objective of underwriting the construction risk for 10 nuclear power plants. This loan program is but a small component of loan guarantees totaling some $1.1 trillion of which some $77 billion in loan authority is directed at clean energy projects, those that emit relatively few greenhouse gases.

In contrast to the $787 billion economic stimulus package and the $75 billion loan modification program, loan guarantees do not automatically lead to a disbursement of taxpayer money. But guarantees are a subsidy and have the potential for payout. In the current fiscal crisis, it is unclear just how much guarantee the government can provide going forward and its willingness to pay should a default occur.

In June 2005, CBO produced a cost estimate for the Senate Committee on Energy and Natural Resources related to their consideration of revisions to the 2005 Energy Policy Act.[3] This estimate covered a variety of loan guarantees under consideration, including projects involving coal degasification, renewable energy, ethanol, and nuclear plant construction. CBO observed the subsidy cost of loan guarantees could vary widely depending on the terms of the contracts and the financial and technical risk associated with different types of projects. Quoting Standard and Poor's, CBO estimates the cumulative default risk for projects rated as speculative investments can range from about 20 percent to almost 60 percent, depending on a project's cash flows and contractual terms. CBO defines the term "subsidy" to mean the net present value of the anticipated cost of defaults, net of recoveries. A $2 billion loan

[3] Congressional Budget Office, "Cost Estimate for S.10, Energy Policy Act of 2005," June 9, 2005, http://www.cbo.gov/ftpdocs/64xx/doc6423/s10.pdf

guarantee for a nuclear construction project was estimated to have a 30 percent subsidy associated with a default event. That is, this would be about $600 million.

Two years later, CBO provided a revised cost estimate to the Senate Committee on Energy and Natural Resources related to their consideration of the Energy Savings Act of 2007.[4] In its analysis, CBO noted the "significant technical and market risks" presented challenges and constraints estimating the subsidy making it "likely that DOE will underestimate than overestimate" cost of insuring against credit risks.

In May 2008, CBO analyzed the effects of Energy Policy Act incentives with special attention to the production tax credit and a loan guarantee program.[5] The tax credit provides up to $18 in tax relief per megawatt hour of electricity produced at qualifying power plants during the first eight years of operation. CBO assesses that generating electricity with nuclear technology would be roughly 35 percent more expensive than using conventional coal technology and 30 percent more expensive than using natural gas capacity. CBO concludes that investment in nuclear capacity would be unlikely in the absence of carbon dioxide charges and Energy Policy Act incentives. CBO explains the reason for the deficit growth: Medicare and Medicaid continue to increase by two to three times the rate of everything else in the economy. Unchecked, these line items will eventually take up every dollar of tax revenues raised, leaving no money for anything else, including national defense.

The Federal government's ability to subsidize energy projects of this magnitude is limited. Actual debt-funded spending currently exceeds receipts, resulting in monthly debt additions of approximately $34 billion. As this is a 9 percent compound annual growth rate, such a debt addition rate requires GDP to increase by about an unrealistic 7 percent annually just to stay at about 100 percent debt/GDP in 2020. Even if U.S. GDP increases by 2.5 percent each year, this will result in a 2020 Debt-to-GDP ratio of 151 percent, comparable to present-day Greece. At such levels, loan guarantees are as much subject to default risk as any other obligation. In an era when natural-gas fired capacity can be brought on-line in half the time and at half the

---

[4] Congressional Budget Office, "Cost Estimate of S.1321, Energy Savings Act of 2007," June 11, 2011, http://www.cbo.gov/ftpdocs/82xx/doc8206/s1321.pdf

[5] Congressional Budget Office, *Nuclear Power's Role in Generating Electricity*, A CBO Study, May 2008, http://www.cbo.gov/ftpdocs/91xx/doc9133/05-02-Nuclear.pdf

cost of nuclear generation, it is difficult to make a case that the Federal Government should issue bonds to finance loan guarantees for nuclear construction.

What price on carbon emissions would help even the playing field for nuclear power plants?

Some advocates suggest a significant investment in nuclear power plant capacity can make an efficient and meaningful contribution to greenhouse gas reduction. As reported by the U.S. Energy Information Administration (EIA), greenhouse gas (GHG) emissions are expected to grow about 0.3 percent annually through 2035, down from 0.8 percent annually (1980-2008). At this rate, pre-recession emissions will not be reached until 2025. In addition to setting back the need for additional electricity generation, the recession also set back GHG imperatives. In 2008, power generation represented 41 percent of the emissions. Coal's 48 percent market share accounts for 82 percent of power sector CO2 emissions. However, coal-fired generation is currently being displaced by natural gas capacity, which would emit roughly half the amount of GHG emissions. While substantial nuclear construction might further cut into the coal plants' emissions, it won't begin to displace coal for some years to decades to come.

To make the economic argument for nuclear requires a reliable forecast of carbon prices. Just as 1960s-era forecasts of nuclear construction costs were unreliable, it is just as difficult to forecast the value of carbon emission offsets 10 years from now. Historic data from the Chicago Climate Exchange demonstrates extreme volatility in carbon markets with prices ranging by factors of 20 or more. Before its acquisition by the Intercontinental Climate Exchange (ICE), the April 2010 open interest, or intensity of trading, in the Chicago Climate Exchange's futures and options contracts totaled some 114,064 contracts. By comparison, in April 2010, CME Group, the leading firm for futures and options trading and risk management, reported a volume of 5,740,439 futures contracts for natural gas physically priced at Henry Hub, the pricing point for natural gas futures. And even as deep and liquid as the natural gas market is, it becomes illiquid for deliveries about a year or more out. The high volatility of carbon markets and low open interest means any forecast of carbon-offset prices for next year is highly speculative - carbon prices 10-30 years from now are mere guesses.

What financing models are effective? Is the United States going about financing nuclear power plants the wrong way? How can the United States do a better job?

The ability to finance any long-lived asset requires a viable bond market. Financing models may apportion the risk in various ways but the cost of this risk capital is ultimately "baked" into the cost of capital. To do a "better job" requires policies aimed at fostering a stable, deep, and liquid bond market. Such markets require stable Federal Reserve policies, low corporate tax and capital gains rates, a strong currency, and stable growth. These conditions favor long-term investments in projects because the cash streams are more predictable and the returns are commensurate with the risk. Under such conditions, credit markets are subject to fewer artificial constraints, less concentration (buy or sell side), and less uncertainty regarding sovereign intervention.

The deficit spending policies in place today do very little to create a viable bond market. Presently, the United States increasingly generates most of its capital through monetization policies that are ending with the Quantitative Easing program in the summer of 2011. The Federal Reserve Bank is the largest holder of U.S. debt and sets interest rates. The ability to finance nuclear power plants, therefore, is ultimately sensitive to the quality of the balance sheet of the United States. As the U.S. deficit grows, the supply of U.S. Treasury bonds will grow. As U.S. Treasury supply grows, corporate debt is either displaced or priced at a premium. In this market in which the United States commands an ever larger market share of long-term debt, the ability to finance nuclear power plant construction outside of a Federal loan guarantee will be increasingly limited.

In summary, policies at the state and federal levels might be engineered for efficiency and fairness well into the future. But company executive teams decide and act today based on their perception of risk, their liquidity, and their available risk capital. Their decisions often make moot the analysis and speculations of market conditions in the distant future. With high deficits under current Federal spending policies, utility balance sheets will continue to suffer and remain poorly positioned to commit to high cost construction projects that won't come on line for a decade in the future.

Chapter 3

LICENSING AND REGULATION OF U.S. NUCLEAR POWER PLANTS

by Albert V. Carr, Jr.

The regulation of the United States nuclear power industry arguably is the most pervasive regulatory system of any in the world. Development, implementation and conduct of that regulatory environment have followed a difficult and convoluted path over the years. In each stage of its development the nuclear regulatory and licensing process has reflected substantial tensions among its various constituents. The first was the conflict between the national security interests of the nuclear weapons program and its absolute governmental control of nuclear materials and technology and of those private entities that sought to develop the peaceful use of nuclear energy for generation of electric energy.[6] Those tensions were to a major extent relieved by the Congress with passage of the Atomic Energy Act of 1954,[7] which established a framework for development of the domestic nuclear power industry. The 1954 Act served as the basis for the Atomic Energy Commission's (AEC) bifurcated licensing process that set the framework for the licensing of the 104 commercial nuclear power reactors now operating in the United States. That licensing process was anything but smooth. Substantial tensions existed among the AEC and its successor agency, the Nuclear Regulatory Commission (NRC), the applicants/licensees and members of the public. Actions taken thereunder arguably increased substantially the costs of plants coming into service and resulted in the dearth of orders for new domestic plants for more than 25 years. As the present generation of plants came into service the NRC put into place a regulatory environment that governs all aspects of the day-to-day operation of the plants that it has licensed. Recent legislative and regulatory changes to the earlier licensing process have hopefully cured many of its defects and may well lead to an environment in which the domestic nuclear power industry can revive.

---

[6] George T. Mazuzan and Samuel Walker, *Controlling The Atom, The Beginnings of Nuclear Regulation, 1946-1962,* University of California Press, (1984), (hereinafter Mazuzan and Walker) at Chapters I-III.

[7] Atomic Energy Act of 1954, 42 USC Sec 2011 *et seq.,* Public Law 83-703 (68 Stat 919).

The Early Days

It is of course no secret that the initial uses of nuclear energy were in weapons development. However, from the early days following the end of World War II, increasing numbers of policymakers and scientists sought to find alternate peaceful uses for nuclear energy.[8] Though a number of uses were considered, including nuclear-powered merchant vessels and aircraft, ultimately the major usage of nuclear energy for peaceful purposes has been in the generation of electricity. The story of how that came to be is interesting, indeed fascinating, in a number of respects.

To begin, the initial task was to overcome the reluctance of the stewards of the nuclear weapons program to share nuclear technology and materials with civilian entities. Once those concerns were met, with considerable prodding from the then-nascent industry, if not alleviated at least accommodated in the Atomic Energy Act of 1954 (The "'54 Act" or the "Act"), the task faced by the agency was formidable, as it had to put into place an entire licensing and regulatory regime to deal with a completely new industry — nuclear power plants.[9]

At the outset, the AEC faced a quandary, as the Act placed squarely on it the responsibility both for developing the peaceful use of the atom and at the same time regulating its usage. This potential conflict-of-interest would plague the agency though it was eventually addressed by setting up a separate office within the agency – the Regulatory division – in a location with its own management and legal offices, particularly as its licensing actions became more controversial and received greater scrutiny by the public. This situation continued until 1975, when Congress enacted legislation that separated the functions, establishing the Nuclear Regulatory Commission as a separate and independent regulatory agency.[10]

Licensing the Initial Plants

The '54 Act put in place a licensing process that while understandable in the context of the early days of the nuclear power industry, ultimately proved to be an impediment to its development. Put briefly, the licensing process established by the '54 Act and its im-

---

[8] Mazuzan and Walker at Chapters I, III.

[9] Id.at Chapt III, Pp.60ff.

[10] Energy Reorganization Act of 1974, 42 USC Sec 5801 *et seq.*, Public Law 93-438 (88 Stat. 1233).

plementing regulations[11] put in place a two-stage licensing process. First, the applicant was required to apply for a construction permit, based primarily on a design concept that would authorize construction of the plant. That application carried with it a mandatory public hearing. The plant was then constructed, with most of the design done during the construction phase. Following completion of construction the utility then had to file an application for a license to operate the plant. That application, while not requiring a hearing, did require the agency to offer an opportunity for a hearing. At the outset of nuclear power plant licensing by the Commission, the focus understandably was on the safety aspects of construction and operation of nuclear plants, as that was the focus of the Commission's organic statute.

The AEC's licensing hearings for both Construction Permits and Operating Licenses were conducted before a three-member Atomic Safety and Licensing Board (ASLB), made up of two technical members – generally one was a nuclear or mechanical engineer and the other an environmental scientist – and a lawyer, who chaired the panel. The proceedings were trial-type hearings with the procedural rules based upon the Federal Rules of Civil Procedure. The procedures placed certain standing and substantive requirements on those who sought to participate as a party. They further provided for the full range of discovery practices, including depositions, document requests and interrogatories. At hearing, witnesses were presented by applicants, staff and sometimes interveners. Full cross-examination was allowed, and the Licensing Boards often participated in the questioning of witnesses. Following completion of the hearings, the ASLB would issue its decision, which then went through the Commission's appeal process.

To implement that process the Commission had established a body known as the Atomic Safety and Licensing Appeal Board (ASLAB). ASLAB's task was to monitor and review proceedings before the ASLBs to protect against legal error that could lead to reversal on appeal. This process worked reasonably well for the first generation of plants licensed, such as Duke Power Company's three-unit Oconee Nuclear Station.[12]

---

[11] 10 CFR Part 50, *Domestic Licensing of Production and Utilization Facilities.*

[12] Duke's Oconee Nuclear Station consists of three Babcock&Wilcox Pressurized Water Reactors, each of 850MWe output, originally licensed in the late 1960s and early 1970s. Oconee was the first nuclear plant in the United States to reach a total electric output of 500 million megawatt-hours.

* Calvert Cliffs Coordinating Committee v. United States Atomic Energy Commission, 449 F.2d 1109 (D.C. Cir. 1971).

It was not long, however, before events began to cause the licensing process to unravel and with it usher in the long cessation in nuclear power plant orders in the Unites States. The first of these events came with the passage by Congress in 1969 of the National Environmental Policy Act (NEPA), which required all Federal agencies to consider the impacts of their actions on the environment, to include alternatives to the proposed action, which alternatives included not taking the action proposed. Agency compliance was to be demonstrated by preparation of an Environmental Impact Statement to guide and document that consideration. In the summer of 1971 the Court Of Appeals for the District of Columbia issued its *Calvert Cliffs* decision, which overturned the regulations adopted by the AEC to implement NEPA.[*] That decision embedded environmental evaluations and analyses into the AEC's licensing processes. Though there were some initial problems, the requirements of NEPA, as interpreted by the *Calvert Cliffs* court, were integrated into the AEC's licensing activities and the nuclear power industry seemed to have a bright future.

This was a time in which the demand for electricity was projected to increase in exponential fashion. In response, electric utilities, which have the absolute obligation to plan, construct and operate their systems to meet present and foreseeable load, were in search of additional generating capacity to meet that forecasted load. Due at least in part to federal energy policy, which restricted access to some fuels for electricity generation,[13] a number of those utilities chose the nuclear option. As a result in the early 1970s the AEC was receiving one or more applications for construction permits per month, and the AEC was processing those applications on a rigid schedule which was amended only under exceptional circumstances. Under these circumstances power plant licensing appeared to move forward smoothly.

---

[13] Indeed, as federal policy actively discouraged the use of certain fuels for generation of electricity it can be argued that federal policy thus encouraged the use of nuclear generation. Prior to the 1970s many utilities, particularly in the South, were using significant amounts of natural gas to generate electricity. However, in the late 1960s, shortages of natural gas began to appear as a consequence of federal wellhead natural gas price controls, and by the winter of 1969-1970 these shortages became acute. The FERC's predecessor agency, the Federal Power Commission, required in the early 1970s interstate natural gas pipelines to curtail delivery of gas to electric utilities that would have been used to fuel boilers for electric generation in order that the gas could be used to serve higher-priority needs – residential and small commercial loads. For its part, Congress passed the Energy Supply and Coordination Act of 1974 – signed into law by the president --that, among other things, required the relevant federal officials to prohibit electric generating stations from using natural gas or petroleum products as boiler fuel and further ordered that existing natural gas and petroleum-fueled generating plants be converted to coal if possible. While these events were taking place, in 1970 the Clean Air Act was enacted into law and subsequently amended in 1977,

All was not how it seemed, though. A series of events occurred in relatively short order that imposed unforeseen, and at times insurmountable, stresses on the licensing process. The first of these was well beyond the ability of either the AEC or the nuclear power industry either to anticipate or cure. In the early 1970s the first Arab Oil Embargo occurred. This event caused, among other things, a rapid and substantial increase in energy prices across the board, including in the cost of electricity. This increase in costs led in turn to reduced demand for electricity, which required applicants to stretch out the schedules for plant construction and operation.[14] This extension of construction schedules occurred at a time of great financial vulnerability as in the 1970s and early 1980s inflation was rampant and interest rates were at an all-time high. This resulted in substantially increased carrying costs for the monies borrowed to finance plant construction. These events were out of the control of the AEC and the applicants.

This was not the case, however, with problems associated with design and construction of the newer generation of plants that were the subject of licensing scrutiny. Whereas the earlier plants were all sized in the 800-900 megawatts (electric) (MWe) range, beginning in the early 1970s vendors increased the size of the plants by about a third, to the 1100 MWe–1250 MWe range. The designs for these new reactors, while sufficient to support the applications for and issuance of Construction Permits, required substantial further work during plants' construction. This in itself was enough to cause construction difficulties, but construction supervision and management issues exacerbated design and construction difficulties. Even leaving aside considerations of design, construction of a nuclear power plant is an enormously complicated endeavor. The work force is substantial, in most instances consisting of a myriad of contractors

---

which placed uncertain limitations on the use of coal as a boiler fuel. Against this backdrop and during this timeframe, then, it is not surprising that a large number of nuclear plants were ordered – 128 from 1971 through 1974.

[14] Traditionally a utility may put into its rate base, and recover with a return, costs prudently incurred in constructing facilities necessary to serve its customers; that is, facilities which in the vernacular are "used and useful." Based on the fact that the original forecasts were no longer valid, so the plants would not be needed when originally projected, decisions to extend construction schedules were understandable; adhering to the original construction schedules would have resulted in capacity that was not "needed" when first available, thus raising questions as to whether it could be included in the utility's rate base. See, *e.g.,* 1 A.J.G. Priest, Principals of Public Utility Regulation, 139-190 (1969); Richard J. Pierce, Jr., *The Regulatory Treatment of Mistakes in Retrospect: Cancelled Plants and Excess Capacity,* 132 U. Pa. L. Review 497, pp. 511-517 (1984).

and subcontractors.[15] A number of the utilities that had filed applications for, and been granted, construction permits had little if any experience with managing major power plant construction projects. Thus, those utilities tended to contract for management as well as construction services. Many of these design and construction issues were resolved with the NRC during construction, but in many instances required redesign and additional construction work. These matters, with others, particularly allegations associated with management issues, often became issues at the Operating License proceedings. Nuclear construction work is an intensely monitored, highly documented activity. That is, the recordkeeping and paperwork requirements are formidable and need precise controls to demonstrate to the regulator that all applicable Quality Assurance standards have been met. Strong and effective management control of these issues was an absolute necessity, and lack of that could be a contributor to delays in construction, licensing and operation of proposed nuclear plants.

The problems outlined above with respect to extending design and construction schedules and rapidly increasing costs had a serious adverse effect on the nuclear power industry. Not only were construction schedules extended, but a number of proposed plants were cancelled, both before and after issuance of construction permits.[16] However there was another factor that also contributed to increased costs and delays. In March 1979 the accident at Three Mile Island occurred. Though the factors already discussed were contributing to industry decline, the TMI accident brought the NRC's licensing activities to an absolute halt. During the hiatus, the NRC reviewed many design elements at plants in the construction phase and, notwithstanding that design and installation of plant systems had received NRC approval, required redesign and construction. This was of and in itself incredibly expensive. When added to the already-inflated costs of plants in the licensing pipeline, the effect of the increased costs for redesign and added delay was stunning, far exceeding the initial estimates for plant construction.

---

[15] At peak work times, the number of construction workers on site at a typical nuclear project could number in the multiple thousands with hundreds of contractors and subcontractors.

[16] In the final analysis, more than 100 proposed nuclear plants were cancelled between 1974 and 1982. *See* Pierce at pp. 497-499.

In fact, a number of the problems associated with design and construction issues, as well as Quality Assurance program sufficiency and documentation came to the fore when many plants filed applications for operating licenses. Public interest groups contested those applications. Allegations of management pressure to comply with construction schedules at the expense of quality assurance measures required attention to both management and to quality assurance documentation. In many instances lack of proper quality assurance documentation combined with construction-related issues presented significant licensing challenges. In most cases these issues added delays and cost to plant completion. In two instances, nuclear plant applicants abandoned their attempts to obtain operating licenses for nearly complete plants and converted them to other fuels for the generation of electricity. One was Consumer Power's Midland, Michigan, plant. In 1984 Midland, a two-unit PWR plant, had been under construction for more than 15 years, was only about 85 percent complete and Consumers had invested almost $4 billion in the project. Faced with sinking and cracking of buildings due to subsidence on the site, quality assurance issues, and TMI-related design uncertainty, Consumers cancelled the nuclear plant and converted Midland to what was then the largest gas-fired cogeneration plant in the world. That plant went into service in 1991. The second was Cincinnati Gas and Electric's Zimmer plant. In 1983 Zimmer had been under construction for about 10 years and was claimed to be 97 percent complete. Its owners had invested about $1.8 billion in the plant, and because of significant quality assurance issues, the NRC had issued a stop work order in 1982. The plant's owners received an estimate of an additional $1.5 billion to complete the plant and obtain the operating license. Zimmer was cancelled in 1983 and converted to a coal plant, at a cost of just over $1 billion, and went into service in 1991.

In the same view, two examples will suffice to demonstrate the magnitude of the cost overruns. Long Island Lighting and Power's Shoreham Plant, a single-unit General Electric plant in the 800 MW(e) range, was initially estimated to cost in the neighborhood of $217 million when its construction began in 1968. Continued licensing delays and NRC redesign and construction requirements as well as delays in operation caused the final cost for Shoreham to be in the neighborhood of $6 billion by the time it was ready to operate in 1984.[17] The Wolf Creek plant, located in Kansas and

[17] Though Shoreham construction was completed and fuel was loaded to permit law-power testing, Shoreham never received an operating license and thus never went into commercial operation. Its ownership ultimately was transferred to the State and the plant was decommissioned.

owned by three Kansas utilities, a single Westinghouse unit of approximately 1200ME(e) capacity, was initially estimated to cost about $525 million when its application for construction permit was filed in 1973. By the time its application for an operating license was filed more than 10 years later its final cost was more than $3 billion.

Neither Wolf Creek nor Shoreham was a particular outlier in terms of final costs of construction far outpacing the original estimates. Wolf Creek (as did the other plants completed with significant cost overruns) presented its State regulators with difficult issues to resolve in placing its investment into rate base so the costs incurred could be recovered from its customers. If the regulators allowed all the money invested to build the plant to be placed into rate base, retail customers could see a tripling or quadrupling of their rates.[18] Thus, state regulators adopted proceedings, generally referred to as "prudence" hearings, to determine how much of the investment should be disallowed and how much should be recovered from ratepayers. Again, Wolf Creek is illustrative. After the State legislature and the State courts were finished with their evaluations,[19] the Wolf Creek investment was treated as follows: A total of $183 million was disallowed on the grounds that these expenditures were imprudently made. No recovery of this amount or return on this investment was permitted. Of the remaining investment, no return was then permitted on $944 million as the Kansas Commission concluded that the capacity and energy represented by this investment was excess to the then-current needs of the system and thus was not "used and useful." The Commission did determine, however, that as system load grew into the capacity over the years that the company could file additional rate cases to seek a return on the investment. The Kansas Commission also determined that portions of Wolf Creek capacity represented "excess economic capacity" and disallowed recovery of $266 million on this basis.[20] Clearly this was not the desired outcome for Wolf Creek or many of the

[18] See *Kansas Gas and Electric Company* v. *State Corporation Commission of Kansas,* 720 P2d 1063 (Kan. 1986) at pp. 1069-70.

[19] Ibid.

[20] Briefly, "excess economic capacity"is determined based on an "economic evaluation" of the plant. The theory is that even if excess physical capacity exists, the plant should be evaluated against a hypothetical competing method of generation – in the case of Wolf Creek a hypothetical coal plant was used – built at the same time. If the cost of capacity from Wolf Creek was found to be higher than the cost of a similar block of capacity from the hypothetical coal plant, then the difference represented "excess economic capacity" and should be disallowed. See *Ibid*, pp. 1084-87.

other nuclear plants – and they were numerous[21] — across the country that received similar treatment. Such disallowances and other variances of recovery of shareholder dollars invested by utilities hardly served as an incentive for utilities to invest in additional nuclear power plants.[22] Taken together, this confluence of events effectively put an end to the ordering of new nuclear power plants in the United States for a period of more than 30 years.

A Nuclear Revival

Over the interviewing years, the industry, the Congress, and the NRC have taken a number of steps to aid in reviving the domestic nuclear power industry. A combination of enabling legislation and regulatory action has put into place a framework for licensing and regulation of a new generation of nuclear plants that, it is hoped, will lead to a "nuclear revival." There were and are a number of drivers behind this effort. One is that though the early operational experience of the 104 reactors that ultimately were brought into service – about 20 percent of our present domestic generating capacity – was not particularly good, over the past two decades their performance has been exceptional. Another is that there is an increasing need for additional base load generating capacity, which matches well with the capabilities and operating characteristics of nuclear plants. Also, there are likely to be increasing environmental restraints on carbon emissions; an operating nuclear power plant does not emit greenhouse gases. Moreover, nuclear power plants hedge against volatility in prices of competing fuels, particularly natural gas. Finally, additional nuclear power plants will aid in domestic energy security.

An examination of the legal and regulatory changes now in place shows that they are intended to remove many of the previous uncertainties from the licensing process to try to spur interest and investment in new domestic nuclear power plants. In brief, they include a new licensing process before the NRC, federal loan guarantees, federal "insurance" against licensing delays and credits for certain electricity generated by nuclear energy.

---

[21] See generally Pierce,132 The University of Pennsylvania Law Review 497 (1984).

[22] The issues associated with recovery of investment in nuclear plants placed into service were not the only matters that vexed financial regulators. Utilities had invested more than $10 billion in nuclear plants that had been cancelled. Those investments were subjected to a variety of regulatory treatments. *Id* at pp 498-500.

The NRC's new licensing environment, codified in 10 Code of Federal Regulations (CFR) Part 52, will reduce substantially the risks associated with the first generation of nuclear plants described above. Rather than the NRC's previous two-stage licensing process that placed significant regulatory and financial risks on the applicant and the vendor, the NRC now has in place a process that melds three component parts into one.[23]

The concept behind Part 52 provides for preapproved standard reactor designs and sites. An applicant can take an approved reactor design, add to it a pre-approved site and then file an application for a Combined License, or COL. The applicant may include design certification and/or site review in the COL process, at its option. The COL is a one-step process with a hearing that should move more smoothly than in the past, while protecting the rights of those involved.[24] This new process also allows for more meaningful and effective public participation. Whereas under the previous process the public participated at the construction permit stage, before much of the information associated with reactor design and operation was available, and/or at the operating license stage, after the plant had been designed and built, and the substantial financial investment made, the new system allows for public participation in all three stages at the outset of each, when that participation can be most effective. The application for an Early Site Permit carries with it a mandatory public hearing. The proceeding for Design Certification is a public process, and public participation is permitted through a "notice and comment" hearing process. Finally, the COL itself requires a mandatory public hearing and the public may participate there as well. The sum of the NRC's revised licensing process is, of course, that an applicant is not required to make substantial financial or organizational commitments until (i) it knows it has an already-approved reactor design as a part of its application; (ii) a site that also is approved; and (iii) a license in hand before it has to make the financial commitment necessary to construct and operate the plant.[25]

The new licensing process has a number of advantages over the old. Rather than changing regulatory standards and requirements, there is a much more stable

---

[23] 10 CFR Part 52, *Licenses, Certifications, and Approvals for Nuclear Power Plants.*

[24] See 10 CFR Part 2, Appendix L

[25] Current projections are that for the new generation of nuclear plants, a two-unit station will cost in the neighborhood of $14 billion to $18 billion.

regulatory regime including an already-approved reactor design. Moreover, the industry learned much about construction of operating plants, not only from those domestic plants built in the 1970s and 1980s, but those built overseas in the last 20 years. Those lessons will be put to good use in current domestic construction. Finally, the present generation of plants is a much more mature technology than was the case in the earlier years.

Congress, in the Energy Policy Act of 2005 (EPACT05) included provisions also designed to encourage investment in nuclear power. First, EPACT05 includes loan guarantees for investments in low-carbon emitting technologies, and those guarantees, which can cover up to 80 percent of project cost for technologies, including nuclear, are a major reason that those moving forward with proposed plants are willing to do so.

EPACT05 also includes provisions for production tax credits for new nuclear capacity added through 2021. Subject to a limit of $125 million per 1000 MW(e) per year, and limited to the first 6000 MW(e) added per year. And finally, EPACT05 includes "Standby Support" provisions that are intended to protect license applicants from delays in the licensing process, such as NRC or litigation delays beyond an applicant's control, during plant construction up until commercial operation.

The question is whether there is at present a nuclear revival in the United States. The answer is a cautious "yes." At present, six applications for Early Site permits have been filed. Four have been approved and five are still under review. Nine applications for reactor design certification have been filed. Four of these have been approved and two are still under review. Most tellingly, 20 different applicants have filed with the NRC 18 COL applications to construct and operate 28 reactors at 18 sites around the United States. Plant Vogtle, owned by Southern Company and Oglethorpe Electric Cooperative, is furthest along in the COL process and actually has begun limited construction at the site. All signs appear encouraging at this point.

Chapter 4

SAFETY OF NUCLEAR POWER

by John F. Ahearne

Are nuclear reactors safe? Are they safe enough? What is meant by "safe," and how safe is safe enough?

Soon after the 1942 nuclear experiments at Chicago's Stagg Field, Enrico Fermi expressed a concern that remains whenever reactor safety is discussed: "The public may not accept an energy source that is encumbered by vast amounts of radioactivity, and that produces a nuclear explosive, which might fall into hostile hands."[26]

The public's safety concerns were exacerbated by the 1979 TMI and 1986 Chernobyl accidents. The TMI accident destroyed the reactor and did not cause any physical harm from radioactive releases (which were small). But it traumatized many thousands. The Chernobyl accident destroyed the reactor and led to a few dozen near-term deaths of the first responders. It released a large amount of radioactive material, and that release may cause thousands of long-term deaths.[27] The 2011 Fukukshima Daiichi accident has caused public concern, but the long-term implications are far from certain as of this writing.

[26] Quoted in letter from A. M. Weinberg to John Gibbons, Assistant to the President for Science and Technology, August 19, 1997.

[27] Assessment of the delayed (latent) fatalities associated with the exposure of radioactive material released by the Chernobyl accident indicates numbers up to 33,000 over the next 70 years assuming a linear non-threshold effect of radiation….on this basis, natural background radiation would result in 1,500 times as many deaths…over the same timescale so these additional fatalities, if the occur, would be very difficult to observe. *Comparing Nuclear Accident Risks with Those from Other Energy Sources*, Nuclear Energy Agency No. 6861, OECD 2010.

Definitions

According to Remy Carle, a senior executive with Electricité de France:

> Nuclear safety encompasses all the technical and organizational measures to be taken to ensure that operation of a nuclear installation has no harmful consequences for public health and the environment. Nuclear safety is based on an approach known as 'defense in depth' which involves:
>
> - accident prevention, from the initial design stage, through careful sizing of all installations, the taking into account of possible equipment failures and human error, the taking into account of external hazards, the implementation of safety systems, and the quality control of the design and execution of equipment and work;
> - continuous monitoring during operation, according to procedures monitored by national authorities;
> - implementation of safety systems to maintain the cooling of nuclear fuel and prevent the release of radioactive products in the event of abnormal operation; lastly
> - definition of emergency planning and procedures to deal with the highly improbably event of a serious accident. [28]

As will be described later, new, enhanced safety features are incorporated in current reactor designs and will continue to be important components of future reactors. The industry has been concerned about what to call these new plants. Should they be "inherently safe," "passively safe," "transparently safe," or some other term. "Naturally safe" received the votes of 44 percent. One term did receive more: 49 percent thought favorably of the term "safer."[29] I doubt this will be the term used by industry, for a reason described later in this article. According to Alvin Weinberg, a "founding father" of U.S. nuclear energy programs, 'inherently safe' reactors – depends "not on the intervention

---

[28] Remy Carl, *Nuclear Power* (Presses Universitaires de France, 1994).

[29] *Post TMI: What Have We Learned*, J.F.Ahearne in Nuclear Safety 1989 Conference Proceedings.

of humans or of electromechanical devises but instead depend on immutable and well-understood laws of physics and chemistry."[30]

A Fundamental Safety Principle

The International Atomic Energy Agency (IAEA) has produced many documents addressing reactor operations. A key point from a 1988 IAEA guide is:

> Fundamental Principle 3.1.2: The ultimate responsibility for the safety of a nuclear power plant rests with the operating organization. This is in no way diluted by the separate activities and responsibilities of designers, suppliers, constructors and regulators. [31]

This became an issue in the aftermath of the TMI accident. A federal court agreed with the NRC that the plant operator had the fundamental responsibility for the safe operation of the plant.

Methodologies to analyze safety[32]

A. Overview of the general approach used to achieve high levels of safety in reactor design and operation.

There is a broad international consensus within the reactor-safety community concerning the key elements that are necessary in the design and operation of a nuclear power reactor to achieve a very high level of safety. While the presence of these key elements generally should provide a high level of safety, the absence of one or more of them is always a cause for concern. Here the phrase "a high level of safety" means a very low probability of an accident that might cause death or injury to offsite populations

---

[30] Inherently Safe Reactors and Second Nuclear Era, A. M. Weinberg and I. Spiewak, Science, 6/20/84

[31] Safety Series No. 75 – INSAG-3, IAEA 1988

[32] Extracted from Nuclear Energy: Present Technology, Safety, and Future Research Directions: A Status Report, J. Ahearne, *et al.* (the primary author for the safety section was R. Budnitz), American Physical Society Panel on Public Affairs, 2 November 2001.

due to radioactivity, or might cause important contamination of offsite land and property. It also implies that the risk to onsite workers and the risk of damage to the facility itself are of acceptably low probability because the elements needed to achieve these are very much congruent with the elements needed to protect offsite populations and property.

[I]t is important to describe in broad terms the safety-engineering challenge.... [F]or a reactor to be acceptably safe it is necessary to assure under all potential upset conditions (a) that the nuclear chain reaction can be shut down and maintained in a shutdown condition [reactivity control]...and (b) that the thermal energy (heat) in the reactor, both heat present at the onset of the upset and heat generated by the continuing radioactive decay processes in the core, is removed to a safe ultimate heat sink.... If both of these can be accomplished in an accident, the radioactivity within the reactor can be contained; if they cannot, it will not be. While other crucial functions, such as the containment function and the emergency-protective-action function, need to be accomplished as back-ups in case these vital functions fail, the most important aspects of preventing harm from the radioactivity are the functions of reactivity control and heat removal.

Different reactor designs accomplish these vital safety functions in different ways.... [A] design is preferable – that is, it is generally "safer" or, at least, more "demonstrably safe" – to the extent that each of these functions is accomplished by relying more on physical principles and passive features and less on active equipment and human intervention. This does not mean that a reactor design relying mainly on active equipment and human intervention cannot be made acceptably safe, but it does mean that there is a broadly accepted hierarchy in which designs incorporating physical principles and passive features to accomplish the vital safety features generally are preferred.

A number of quite new reactor designs are now under active development. Many of them claim as explicit advantages that they rely more on physical principles and passive features to accomplish the key safety functions. The key elements that are necessary in the design and operation of a nuclear power reactor to achieve a very high level of safety are the following:

a) A strong base of both scientific and engineering knowledge to support each aspect of the reactor-safety program.

b) A reactor design that accounts for all important potential accident scenarios by employing systems and operational features that reduce the probability of each such scenario, or reduce its potential consequences (or both) to acceptable levels; and the ability to analyze that design well enough to provide high assurance that the above is achieved.

c) A reactor design that uses established codes and standards and incorporates adequate margins to assure acceptable performance in light of the uncertainties in knowledge.

d) A reactor design that incorporates a defense-in-depth safety philosophy to maintain multiple barriers, including both physical and procedural barriers as appropriate.

e) A reactor design that uses a philosophy of redundant and diverse safety systems to assure highly reliable performance during all potential accident scenarios.

f) A reactor design that incorporates technical specifications that conservatively define, control, and circumscribe a safe operating envelope.

g) An adequate basis, in experiment, theory, and testing, to support the design specifications and the safety analyses used for safety assurance.

h) The use of quality materials, quality manufacturing of equipment, and quality construction and maintenance practices.

i) An operating philosophy that embodies a profound respect for the possible dangers inherent in reactor operations.

j) A staff of qualified operating and maintenance personnel, supported by a management committed to a strong organizational safety culture, and also supported by a strong engineering capability.

k) An ability to analyze the safety achieved by the operation, in terms of both realistic probabilistic analyses and conservative engineering analyses of the as-built-as-operated facility; and an ability to use the information from such analyses to maintain and enhance safety.

l) Emergency plans that adequately protect offsite populations.

m) An operational safety culture that is both comprehensive and managed properly, and that incorporates an effective self-assessment and corrective-action program.

n) A system that derives safety insights from operating experience and from analyses performed both within the reactor organization itself and elsewhere around the world, and that applies these insights effectively.

o) A strong management organization with both the resources and the motivation to maintain all of the above.

p) An arrangement that has access to a continuing program of nuclear safety research, and that uses the insights derived from that research for safety improvement.

q) An independent regulatory authority that is responsible to the government and the public for overseeing safety, and for taking corrective or enforcement actions as necessary.

Over the past thirty years, international operating experience has demonstrated the importance of high-quality engineering of the facility and high-quality human performance…[O]perator qualifications and training must be supplemented by operating procedures for both normal and abnormal/emergency situations, and by procedures for accident mitigation. All of the above must be embedded in a strong safety culture, to ensure that each element of the entire safety envelope is maintained. Said another way, the basic safety values and attitudes of the operating entity, from top to bottom, can be as important as the basic design — inadequacies in either can lead to a degradation of safety.

Many countries deploy nuclear power reactors that achieve very high safety levels because all of the elements above are present and are maintained. It is in this sense that the nuclear-engineering community believes that adequate safety levels have been achieved in these countries. The IAEA has assisted in upgrading the conduct of operations in many of its member countries.

B. Overview of methodologies used to assess the probability of accidents (severe and "moderate")

In the early days of reactor operation, the methods used to assess how well safety was achieved were qualitative rather than quantitative because no analytical methodology existed that could provide quantitative estimates of the risks. This also is true for many other complex technological endeavors (manned space travel is another example) where severe accidents are concerns but occur too rarely to provide an evidentiary basis for estimating the risks.

In the nuclear-power arena, a very capable methodology has evolved that now provides a strong technical basis for such safety assessments. This is the "probabilistic risk assessment" (PRA) methodology. The PRA methodology essentially involves writing down in the form of "event trees" each of the important accident sequences (from initiating event to core damage to radioactive release) that might result in a major accident, and then analyzing the likelihood of each sequence using logic, equipment reliability data, human reliability data, an understanding of the correlations among failures, an understanding of the physical phenomena in each scenario, and a wealth of design and operational information. Originally, the PRA methods were developed to deal with accidents initiated by internal equipment faults and human errors. Today, the methods can also deal well with potential accidents initiated by internal fires, external phenomena such as earthquakes and tornadoes, and upset conditions occurring during shutdown conditions as well as at full power.

For analyzing the probabilities and consequences of power-reactor accidents, the methodology has reached a state of maturity in which it is now routinely used by both the operating entities and the safety regulators worldwide as a continuing check on how well each of the major elements of reactor safety is achieved.

However, the PRA methodology cannot provide highly accurate estimates of the probabilities and consequences of the major accidents of concern: some of the underlying data and models are not known well enough to support such a very accurate estimate. Hence the uncertainties in the "bottom-line" numbers for the annual core-damage frequency, or the likelihood of a specified large radioactive release of a certain size and character, are often as large as plus-or-minus an order of magnitude or more.

Therefore, the major use of the PRA methodology is not to produce such "bottom-line" assessments, important as they are in providing an overall understanding of the safety levels achieved. Rather, the principal applications of PRA are to enable the analyst and the safety decision-maker to understand which elements of the overall system contribute how much to safety, and why; and to study the effect on overall safety of changes in the system (be they undesired changes due to equipment failures or human errors, or planned changes such as scheduled maintenance that may temporarily compromise part of a safety function).

It is important to emphasize that the methodology of PRA, which was originally developed to assess the overall probabilities and consequences of major undesired power-reactor accidents, does indeed provide such assessments and that these assessments are of broad use to policy-makers, despite the large numerical uncertainties in the bottom-line risk numbers. In most countries around the world these bottom-line risk numbers are judged acceptable by regulatory authorities, providing the context for the rest of the work that reactor-safety professionals do in maintaining and improving reactor safety.

Another major use of PRA methods is to assess the effectiveness of the overall design and operation, by highlighting where additional equipment or modified procedures can enhance safety. Also, PRA can identify where it would be feasible to relax strict engineering/maintenance standards for equipment that was originally thought to be "required for safety" using traditional engineering principles, but that in fact contributes little to safety; such relaxations can simplify operations or save on human or capital resources. PRA helps to establish optimum preventative maintenance programs by focusing on the risks associated with equipment/system failure. The application of PRA in maintenance, called "reliability-centered maintenance," identified cases where increased preventative maintenance was needed, as well as cases where relaxed preventative maintenance was appropriate. Another major use of PRA is to allow the regulatory authority to concentrate its own resources on those design or operational aspects that contribute most to the safety of a given reactor facility, for example by guiding regulatory inspectors about "where to look." PRA also can highlight areas where not as much is known as we would like – thus motivating development of new knowledge, either knowledge from operating experience or knowledge through advanced research.

It also is useful to recognize that, although PRA methods are mature enough to be used routinely, there are important areas where additional PRA-methodology research could be of benefit. These include our limited understanding of how to analyze and affect the role of safety culture and management as it influences reactor safety; our incomplete understanding of human performance under stress, including errors of commission and errors of cognition; our limited understanding of how certain correlations among failures may affect safety; and our need for more realistic models of the detailed behavior of radioactive materials inside the facility in some accident conditions. Further, the understanding of the effects on human health arising from potential reactor accidents is severely limited by the incomplete understanding of the dose-response relationship for radiation doses well below those that produce short-term clinical effects. Because of knowledge limitations, the reactor-safety-analysis community has always applied dose-response models more suited to radiation protection than to realistic assessment. All of these areas could benefit from the development of new knowledge or new analysis tools, or both, which is the purpose of reactor safety research.[33]

History

According to NRC historians, overall, the nuclear industry had an excellent reactor safety record, due undoubtedly to the design and procedural requirements placed on it as well as the research on safety questions. This track record notwithstanding, with the increased public scrutiny of both the industry and the AEC in the 1970s, the probability of a major nuclear reactor accident loomed as a distinct threat to many critical minds. The AEC had Brookhaven National Laboratory conduct a study to provide an estimate of the upper limit of the consequences that might be involved in a reactor accident. Report WASH-740 estimated that personal damage might range from no injuries or fatalities to approximately 3,400 killed and 43,000 injured. The Rasmussen Report's or WASH-1400's objective was to make a realistic estimate of public risk

[33] End of APS material

involved in potential "class 9" accidents (accidents that could lead to radiological consequences outside plant boundaries that would exceed AEC regulations). The basic conclusion of this complex study suggested that risks to the public from potential nuclear accidents were small compared to other forms of risk in a complex technological society. The conclusion of the report states, "It will take consideration by a broader segment of society than that involved in this study to determine what level of nuclear power plant risks should be acceptable."[34]

Presently, according to the Organization for Economic Cooperation and Development (OECD), the theoretically calculated frequency of a severe nuclear power plant accident followed by a large radioactivity release has [been] reduced by a factor of 1,600 between the original designs of early Generation I reactors and the Generation III/III+ plants being built today. It is important to note that the "as originally designed" performance of the earlier plants has also been improved by upgrades over subsequent years.[35]

The Nuclear Energy Institute reported that the nation's nuclear power plants in 2009 had one of the safest industrial working environments and fell just shy of setting a record for reactor efficiency. WANO [the World Association of Nuclear Operators] found that the nation's 104 operating nuclear power reactors reached a median unit capability factor – a measure of a plant's on-line production time – of 91.3 percent.

There were so few unplanned automatic reactor shutdowns per 7,000 hours of reactor operation in 2009 that the median value approached zero. Statistics from other industries through 2008, as compiled by the Bureau of Labor Statistics, show that it is safer to work at a nuclear power plant than in the manufacturing sector and even the real estate and financial sectors. [36]

Other countries with current programs

U.S. NRC regulations have been used worldwide as a starting point for reactor regulation. For example, in Germany, safety philosophy is based on that of the United States

[34] *An Outline History of Nuclear Regulation and Licensing, 1946*-1979, G. T. Mazuzan and R.R. Trask, Historical Office of the Secretary, Nuclear Regulatory Commission, April 1979.

[35] *Comparing Nuclear Accident Risks, op cit.*

[36] Nuclear Energy Overview, NEI 6/11-17/2010

with greater reliance on accident prevention or mitigation concepts.[37] In France, for more than 20 years, there has been an extensive and continuous exchange of information between nearly all safety organizations around the world, either by means of bilateral agreements or under the sponsorship of such international bodies as the International Atomic Energy Agency in Vienna and the Nuclear Energy Agency in Paris. Furthermore, numerous efforts have been made to promote the harmonization of safety criteria in use in various countries, and countless working groups have been set up for that purpose. Consequently international consensus has been achieved on many important safety issues, and gradually the safety philosophies have grown closer.[38]

New Entries

Many countries without nuclear plants have expressed interest in such plants. There are several potential safety problems as these plans progress. An IAEA nuclear safety review this year gave advice on addressing the issues associated with new entrants:

> One striking change from the past is now emerging – namely, the interest in the pursuit of nuclear power by a large number of countries that have no previous experience with power reactors. Safety, on the other hand, is a challenge that every new entrant will necessarily confront. It is an inevitable and on-going challenge at every nuclear site. The creation of a culture that enables the achievement of safety takes persistence, commitment and very hard work and needs to start at the moment that a decision is made to embark on a nuclear power program and endure throughout a power plant's life. It is expensive. And it involves an attention to detail and a willingness to accept and learn from intrusive peer review by others. At the opening stage, the new entrant must establish the legal framework for nuclear activities and create an independent, competent and well-funded regulator with an overriding commitment to nuclear safety. The IAEA safety standards provide crucial general guidance. Practical experience has

---

[37] "The Safety Concept of Nuclear Power Plants in the Federal Republic of Germany," H.L.Schnurer and H.G.Seipel, *Nuclear Safety*, **24**, no.6, Nov. – Dec.1983, pp.743-782.

[38] *The French Approach to Nuclear Power Safety*, P. Tanguy, Nuclear Safety, Sept-Oct 1983

> shown that the availability of high-quality safety standards is not enough to guarantee their effective implementation. Vendors must seek to ensure that a new entrant understands and has the capability to meet its safety commitments.[39]

The need for trained personnel was identified in another review: "For nuclear power to expand in emerging countries will require a massive education and training program to support nuclear power programs."[40]

New Reactors [41]

Reactors with the term "advanced" are currently operating and more are planned. All these are classed as GEN III+. They include the ABWR (advanced boiling water reactor) built in Japan and the Korean APR-1400, modeled after the CE System 80+. The latest is the French EPR being built in Finland and EPR is under construction in Brittany. Japan also is building two large (1540 MWe) advanced pressurized water reactors (APWR) of Japanese design. The Korean reactor exemplifies a clear trend in Asia, where countries are designing and building their own reactors. This is seen in Japan, South Korea, China, and India. For example, in June of 2005, the 540 MWe PHWR Tarapur-4, a reactor designed and built by the Nuclear Power Corporation of India, was connected to the grid.

Using a term of the 1990s, these are evolutionary reactors, improved (often significantly) modifications of existing reactors. The gas-cooled pebble bed modular reactor (PBMR) also is related to previous reactors but with operational experience limited to one German research reactor and a small pebble bed reactor in operation in China, the 10 MWe HTR-10. China has plans to build a 160 Mwe commercial demonstration pebble bed reactor. The PBMR offers small size, gas cycle efficiency, and accident-resistant fuel. The early proponent of commercialization has been Eskom, the

---

[39] Letter to IAEA Director General Amano from INSAG Chair Meserve, August 28, 2010.

[40] "Report from Como: Expanding Nuclear Power to New States – Defining Needs and Exploring Paths to Success," 10-14 June 2008, Como, Italy.

[41] Extracted from "Advanced Nuclear Reactors – Their Use in Future Energy Supply," J.Ahearne, Forum on Physics and Society, April 2006, vol. 35, No. 2.

large South African utility.[42]

Each of the new reactors was designed to be simpler, safer, and have lower cost than currently operating reactors. The passive safety feature reactors rely on gravity, natural circulation, and compressed air to provide cooling of both the core and the containment in the case of a severe accident. This permits a reduction in systems that were designed to force coolant into the system. For example, compared with a typical similar size reactor, passive safety systems in the AP1000 led to 50 percent fewer valves, 35 percent fewer pumps, 80 percent less pipe, 48 percent less seismic building volume, and 70 percent less cable.[43]

> The IAEA recently summarized some of the new reactor developments:
>
> China has already developed and operated its own domestic medium-size PWR designs [and] the China National Nuclear Corporation … has developed the evolutionary China Nuclear Plant (CNP-1000)…
>
> The European pressurized water reactor's (EPR's) power level of 1600+ MW(e) has been selected to capture economies of scale. Electricite de France (EdF) is planning to start construction of an EPR at Penly beginning in 2012. Two EPR units are also under construction in China….
>
> [I]n Japan, MHI [Mitsubishi Heavy Industries] has developed the advanced pressurized water reactor (APWR+)…
>
> In the Republic of Korea, the benefits of standardization and series construction are being realized with the 1000 MW(e) Korean Standard Nuclear Plants (KSNPs). Ten KSNPs are in commercial operation.
>
> In the Russian Federation, evolutionary WWER plants have been designed….WWER-1000 units are currently under construction at the Kalinin and Volgodonsk sites and WWER-1200 units at the Novovoronezh-2 and Leningrad-2 sites.

[42] In September 2010 the government announced the project had been cancelled.

[43] End of advanced reactors article.

> Advanced HWR [heavy water reactor] designs are also being developed in a number of countries. [44]

Will these new plants be "safer"? This was addressed in a recent article:

> It is worth noting that the NRC does not require the new plants to be any safer than existing ones. Rather, it only requires the plants to "provide the same degree of protection" as the current generation of reactors.
>
> Although the new U.S. reactors will have some "design enhancements" – digital controls versus analog dials, for example – "at bottom they are based on familiar and proven technology" says [Nuclear Energy Institute official] Russ Bell.
>
> Will this new generation of reactors be safer than the current nuclear plants? Ask that of the industry's Bell and he chose his words carefully, because to imply that the new reactors are "safer" than the old ones [would] infer that the existing plants are less safe.[45]

Public Perception and Acceptance

Fermi wondered if the public would accept nuclear plants. The safety of these plants has been a constant issue for the nuclear industry's relationship with the public. Polls show the same trend but are not consistent in the overall message.

Gallup: A majority of Americans have been supportive of the use of nuclear energy in the United States in recent years, but [the 2009] Gallup Environment Poll found new highs of support, with 59 percent favoring its use, including 27 percent who strongly

---

[44] "International Status and Prospects of Nuclear Power, Report by the Director General," GOV/INF/2010/12-GC (54)/INF/5, September 2, 2010.

[45] "The Nuclear Power Resurgence: How Safe Are the New Reactors?" Susan Q. Stranahan, *Yale Environment 360*, June 17, 2010.

favored it. Americans may have not fully embraced the use of nuclear energy because of concerns about potential health risks from a nuclear meltdown or the nuclear waste that power plants produce. The poll found that a majority of Americans, 56 percent, believed that nuclear power plants are safe, but a substantial minority of 42 percent disagreed.[46]

Bisconti: In March 2010, three out of four Americans said they favor nuclear energy (74 percent). Also, 70 percent believed that "we should definitely build more nuclear power plants in the future."[47]

MIT: In the five years since the last [MIT] survey in 2002, public preferences have remained fairly stable, but the percentage of people who want to increase nuclear power has grown from 28 percent to 35 percent.[48]

Post Fukushima: Unsurprisingly, public support went below a majority favoring nuclear power.

Conclusion

Following the two major reactor accidents of TMI and Chernobyl, designs have been scrutinized and improved, operating practices improved, and personnel training stressed. Also, during the ongoing Fukushima accident, the NRC has been conducting a review of U.S. nuclear plants. This review may spur further design changes and safety retrofits. Safety remains a mixture of design, construction, maintenance, and what has been called a "safety culture": the need for all involved personnel to stress safety in all their practices. The US NRC has wrestled with "how safe is safe enough" and published safety goals for operating plants.[49] These were designed to explain safety to the public but were not made requirements and have been succeeded by a design requirement for annual core-damage frequency of 10^{-4}, clear to technologists but not transparent to the

---

[46] Jeffrey M. Jones, "Support for Nuclear Energy Inches up to New High," Gallup poll, March 20, 2009.

[47] "Public Support for Nuclear Energy at Record High," Bisconti Research, March 2010.

[48] "Americans warming to nuclear energy – MIT survey," MIT News Office, July 23, 2007.

[49] "Safety Goals for the Operations of Nuclear Power Plants: Policy Statement," 51 FR 30028, 8/21/86. See also "How safe is safe enough?" J.F.Ahearne, *Reliability Engineering and System Safety* ***62***, 1998.

public. New designs rely on passive rather than active systems that have not yet been challenged by an accident. Asia is the location for the large growth in numbers of reactors in the next decade, placing challenges on regulators, education systems, and operator training. What happens in Asia or other parts of the world will likely affect the U.S. nuclear power fleet.

Chapter 5

SECURITY OF U.S. NUCLEAR POWER PLANTS

by Harold A. Feiveson

Commercial nuclear power plants in the United States could be targets for terrorists attempting to release radioactive materials to the environment. According to the 9/11 Commission, nuclear power plants were among the targets considered in the original plan for the September 11, 2001 attacks.[50] In addition to nuclear power plants, other nuclear facilities include civilian research reactors, certain naval fuel facilities, uranium enrichment plants, and fuel fabrication plants. Security at these other nuclear facilities must also be addressed, but this chapter focuses only on security at the commercial nuclear power plants.[51]

The Threats to Nuclear Power Plants

If terrorist groups could sufficiently damage safety systems to cause a core meltdown, such an attack could lead to a massive radioactive release to the environment. An attack on a reactor's spent fuel pool could also be severe, and it is noteworthy that the pools are less well protected than the reactor core. Depending on location and the amount of radioactive material, the release of radioactivity could lead to thousands of near-term fatalities and still greater numbers of long-term deaths. In the year 2000, about one-fifth of the nuclear sites had more than 100,000 people living in the 10-mile emergency zone around the sites.[52]

---

[50] The National Commission on Terrorist Attacks Upon the United States, *The 9/11 Commission Report*, July 22, 2004.

[51] Security at research reactors were the subject of a recent study by the U.S. Government Accountability Office, *Nuclear Security Action May Be Needed to Reassess the Security of NRC-Licensed Research Reactors*, January 2008.

[52] Edwin S. Lyman and David Lochbaum, "Protecting Vital Targets: Nuclear Power Plants," in James J. F. Forest, ed., *Homeland Security: Protecting America's Targets, Volume III (Critical Infrastructure)*, 2006, pp. 157-173.

If nuclear power is to grow substantially, nuclear facilities – especially the numerous reactors in diverse locations — will have to be made extremely safe from incidents that could release massive quantities of radioactivity to the public. New reactor designs have improved safety, partly by incorporating features of passive safety, such as the flooding of the reactor core without active intervention by reactor operators. These safety measures have generally been developed and studied with respect to accidents – not to the deliberate attack on a reactor by a terrorist group, which could in principle disable or destroy the various multiple protections against accidents.[53] However, as explained further below, the Nuclear Regulatory Commission does also require new reactor license applicants to consider security during the design stage.

The terrorist threat is of two general types: commando-like ground-based attacks (including different attack modes), possibly abetted by an insider, on some designated target sets, notably equipment which if disabled could lead to a core meltdown or dispersal of radioactivity from the spent fuel pool; and external attacks such as an aircraft crash into the reactor complex or cyber attacks (which may also be initiated via insiders).

Government Oversight of Security at Nuclear Power Plants [54]

Overview. The Nuclear Regulatory Commission (NRC) has the primary responsibility for ensuring that power reactor licensees operate in a secure manner. The NRC is an independent federal agency responsible for licensing civilian nuclear plants and regulating and overseeing their safe operating and security.[55] In discharging this responsibility, the NRC coordinates its security activities with other federal, state, and local law enforcement agencies, including the Department of Homeland Security (DHS), the Federal Bureau of Investigation (FBI), the Federal Aviation Administration (FAA), and

---

[53] Edwin S. Lyman, "Chernobyl on the Hudson? The Health and Economic Impacts of a Terrorist Attack at the Indian Point Nuclear Power Plant," *Union of Concerned Scientists,* September 1994, p. 21.

[54] Three excellent recent overviews are Mark Holt and Anthony Andrews, *Nuclear Power Plant Security and Vulnerabilities*, CRS Report to Congress, Congressional Research Service, March 18, 2009, and updated, August 23, 2010; and Edwin Lyman, "Security since September 11," *Nuclear Engineering International*, March 2010.

[55] U.S. Government Accountability Office, "Nuclear Power Plants: Efforts Made to Upgrade Security, but the Nuclear Regulatory Commission's Design Basis Threat Process Should Be Improved," GAO-06-388, March 2006, p. 12.

others. The DHS in particular supports efforts to enhance security outside of the plants themselves.

The NRC formulates a design basis threat (DBT) that nuclear plant operators have to defend against, and issues and enforces regulations to ensure that the nuclear plants implement appropriate security measures to meet the DBT. The DBT does not represent the maximum size and capability of a terrorist attack that is possible, but rather some plausible threat that the plant operators have to consider in devising physical security arrangements. In particular, the DBT and NRC regulations do not require nuclear power plants to protect against attacks by an "enemy of the United States," whether a foreign government or other person. The NRC evidently decides the dividing line between the design-basis threat and the beyond-design-basis threat.[56] The details of the DBT, including the adversary characteristics, are specified in non-public regulatory guides, so that language in the NRC rule could be compatible with different numbers of attackers and weapons, and these numbers could be increased without a change in the overall rule.

The NRC oversight seeks to ensure adequate power plant performance in five key aspects: access authorization to critical areas of the plant; access control; physical protection systems, such as fences, cameras, and the like; material control and accounting; and response to contingency events.[57] The last aspect refers to commando-like attacks, and is tested by the NRC through so-called Force on Force (FOF) inspections, discussed further below.

Design Basis Threat. It is widely believed that before the September 11, 2001 attacks, the DBT consisted of one team of three individuals assisted by a single passive insider who could provide plant-specific information but not participate in the attack.[58] After 9/11, the NRC and Congress took actions to strengthen the DBT. In 2002 and 2003,

---

[56] Edwin Lyman, "Security since September 11," *Nuclear Engineering International*, March 2010, pp. 16-17.

[57] U.S. Nuclear Regulatory Commission, *Report to Congress on the Security Inspection Program for Commercial Power Reactor and Category I Fuel Cycle Facilities: Results and Status Update*, Annual Report for Calendar Year 2009, p. 3.

[58] Edwin Lyman, "Security since September 11," *Nuclear Engineering International*, March 2010, pp. 15-16.

the NRC worked to revise the DBT, and it approved a revised DBT in April 2003 "to represent the largest reasonable threat against which a regulated private guard force should be expected to defend under existing law."[59] In the Energy Policy Act of 2005, Congress imposed a statuary requirement on the NRC to revise the DBT based on assessments of various terrorist threats worldwide, plausible explosive devices, and the possible use of modern weapons, such as precision-guided munitions. In January 2007, the NRC approved its final rule amending the DBT effective April 18, 2007. It appears that the 2007 DBT is similar to that of 2003, though with some changes that have not been made public. In the 2007 rule, the NRC noted:[60]

> The Nuclear Regulatory Commission (NRC) is amending its regulations that govern the requirements pertaining to the design basis threats (DBTs). This final rule makes generically applicable security requirements similar to those previously imposed by the Commission's April 29, 2003 DBT Orders, based upon experience and insights gained by the Commission during implementation, and redefines the level of security requirements necessary to ensure that the public health and safety and common defense and security are adequately protected. Pursuant to Section 170E of the Atomic Energy Act (AEA), the final rule revises the DBT requirements for radiological sabotage, generally applicable to power reactors and Category I fuel cycle facilities, and for theft or diversion of NRC-licensed Strategic Special Nuclear Material (SSNM), applicable to Category I fuel cycle facilities.[61]

Although the specific details have not been made public, the NRC has clarified that the 2003 DBT "expands the assumed capabilities of adversaries to operate as one or more teams and attack from multiple entry points; assumes that adversaries are willing to kill or be killed and are knowledgeable about specific target selection; expands the scope of vehicles that licensees must defend against to include water vehicle and land vehicles beyond four-wheel drive type; revises the threat posed by an insider

---

[59] *Federal Register*, May 7, 2003.

[60] *Federal Register*, March 19, 2007.

[61] Category 1 fuel cycle facilities are those that use or possess formula quantities of strategic special nuclear material (defined in Title 10 of the Code of Federal Regulations [10 CFR, Section 70.4] as uranium-235, contained in uranium enriched to 20 percent or more in the U-235 isotope, uranium-233, or plutonium.)

to be more flexible in scope; and adds a new mode of attack from adversaries coordinating a vehicle bomb assault with another external assault."[62]

The exact number of attackers in the new DBT is not public. But *Time* Magazine reported in 2005 that the new number incorporated in 2003 was "less than double the old figure and a fraction of the size of the [September 11] group."[63] If that report is accurate, and the final 2007 DBT is close to that of 2003, it would appear that the new 2007 DBT envisions no more than 5 attackers. The new DBT includes a wider range of weapons available to the attackers than previously considered, but apparently with some plausible weapons still excluded. Specific adversary attributes are discussed in a non-public document.

The final DBT rule excluded aircraft attacks, an issue which is discussed further below. Cyber security actions were required by the NRC after 9/11 and subsequently codified through issuance of 10 CFR 73.54 in March 2009. The new regulation "requires licensees to submit a new cyber security plan and an implementation timeline for NRC approval. The plan must show how the facility identified (or would identify) critical digital assets and describe its protective strategy, among other requirements."[64] In January 2010, the NRC published a regulatory guide that provides guidance to licensees on ways to meet the requirements of the regulation. The possibility of cyber attacks on reactors has been made vivid by speculation that the so-called Stuxnet worm, which has recently received attention generated by cyber security experts in Germany, was directed at Iran's Bushehr reactor, as well as the Natanz centrifuge plant.[65]

---

[62] Mark Holt and Anthony Andrews, *Nuclear Power Plant Security and Vulnerabilities*, 2010, p. 3; see 10 CFR 73.1.

[63] Mark Thompson, "Are These Towers Safe?" *Time*, June 20, 2005, pp. 34-48; Lyman, Security since September 11, p. 16.

[64] Nuclear Regulatory Commission, "Backgrounder on Cyber Security," April 2010; Office of the Inspector General, Nuclear Regulatory Commission, Audit of NRC's Force-on-Force Inspection Program, July 30, 2009, pp. 1-2; Nuclear Regulatory Commission, *Report to Congress on the Security Inspection Program for Commercial Power Reactor and Category I Fuel Cycle Facilities: Results and Status Update*, Annual Report for Calendar Year 2009, p. 4.

[65] Mark Clayton, "Stuxnet worm mystery: What's the cyber weapon after?," *Christian Science Monitor*, September 24, 2010; Nicolas Falliere, Liam Murchu, and Eric Chien, "W32.Stuxnet Dossier," *Symantec*, November 2010; see more recently, William Broad, John Markoff, and David Sanger, "Israeli Test on Worm Crucial in Iran Nuclear Delay," *New York Times*, January 15, 2011.

Force on Force (FOF) Inspections and Exercises. The NRC carries out FOF inspections at all Nuclear Power Plant (NPP) sites at least once every three years. The NPP is given notice of an upcoming inspection about two to three months in advance. The FOF inspection, which is typically conducted over the course of 3 weeks, "includes both tabletop drills and exercises that simulate combat between a mock adversary force and the licensee's security force. At an NPP, the adversary force attempts to reach and simulate damage to key safety systems and components, defined as "target sets" that protect the reactor's core or the spent fuel pool, which could potentially cause a radioactive release to the environment. The licensee's security force, in turn, interposes itself to prevent the adversaries from reaching target sets and thus causing such a release."[66] An FOF inspection typically includes three FOF exercises over three nights. "Plant defenders know that a mock attack will take place sometime during a specific period of several hours, but they do not know what the attack scenario will be."[67] Participants carry weapons modified to shoot laser bursts, and wear laser sensors to indicate hits. Other weapons and explosives are also simulated.

Before 9-11, the NRC conducted FOF exercises about once every eight years at each NPP. Starting in 2004, the NRC has undertaken to conduct FOF inspections at each plant site once every three years, with tactical security drills, conducted by the licensees, in the intervening years. This implies about 22 FOF inspections each year. In preparation for the FOF exercises, information from the tabletop drills are factored into the adversary attack strategies. When a complete target set is simulated as destroyed, and the NRC determines that the licensee's protective strategy does not assure protection against the DBT, the NPP has to put in place compensatory measures immediately.

Since October 2004, Wackenhut, the same company that provides security forces to several nuclear plants, has managed the mock adversary force. The NRC acknowledges that this at a minimum creates a perception of a conflict of interest. However, to guard against such a conflict of interest, the NRC requires that no member of the mock adversary group may participate in an exercise at his or her home site; and the NRC emphasizes that it, not the mock adversary group, designs, runs, and evaluates the

---

[66] Nuclear Regulatory Commission, *Force-on-Force Security Exercises*, Fact Sheet, May 2007; Nuclear Regulatory Commission, *Report to Congress on the Security Inspection Program for Commercial Power Reactor and Category I Fuel Cycle Facilities: Results and Status Update*, Annual Report for Calendar Year 2009, pp. 7-8.

[67] Mark Holt and Anthony Andrews, *Nuclear Power Plant Security and Vulnerabilities*, 2010, p. 8.

results of the FOF exercises and that the adversary's performance is subject to continual observation by the NRC.[68] Department of Defense contractors provide support to the mock adversary group in tactics planning.

In 2009, the NRC conducted FOF inspections at 22 commercial nuclear power plants; and by the end of the year, it had completed the second year of the second 3-year cycle of FOF inspections. Cumulatively, from November 2004 through December 2009, the NRC had conducted 112 inspections, 8 of which times a complete target set was damaged or destroyed.[69]

Aircraft attacks. As noted, the 2007 DBT did not include aircraft attacks, and existing nuclear power plants were not required to undertake active protective measures against airborne threats. Nevertheless, in a final rule issued on June 12, 2009, the NRC required applicants for new nuclear plant designs to "perform an assessment of the effects of the impact of a large, commercial aircraft," and "identify and incorporate design features and functional capabilities to show, with reduced use of operator actions," that address such impact. The rule still classifies an aircraft attack as "beyond design basis threat." Also, in addressing the threat of an aircraft attack, the NRC works with other agencies, including the FAA and the North American Aerospace Defense Command (NORAD). In the view of critics, all this does not go far enough. For one reason, new plants will comply with the rule if analysis shows that "either the reactor core remains cooled or the containment remains intact, and either spent fuel cooling or spent fuel pool integrity is maintained." Thus, it might be that containment is not breached initially but the core damaged. Also, it is not clear how spent fuel pool cooling can be maintained if spent fuel pool integrity is violated.[70]

The air crash risk to a power plant is unclear. The Union of Concerned Scientists and other interest groups argue that an air attack could penetrate the containment

---

[68] Nuclear Regulatory Commission, *Force-on-Force Security Exercises*, Fact Sheet, May 2007, pp. 3-4.

[69] Nuclear Regulatory Commission, *Report to Congress on the Security Inspection Program for Commercial Power Reactor and Category I Fuel Cycle Facilities: Results and Status Update*, Annual Report for Calendar Year 2008, and 2009. NRC-2008 reported that for the period November 2004 to December 2008, 4 inspection had resulted in compete target set damage or destruction. NRC-2009 reported 3 such results in 2009, and a cumulative total of 8 from November 2004 to December 2009. It is not clear why the cumulative total was not 4 + 3 = 7.

[70] Edwin Lyman, "Promoting Mediocrity: NRC's Policy for New Facility Security Design," presented at the Institute of Nuclear Materials Management 50th Annual Meeting, Tucson, AZ, July 12-16, 2009.

structure of a nuclear power plant or spent fuel storage facility, causing a core meltdown or spent fuel fire. Nuclear industry people counter that nuclear plants are difficult targets for attack, that penetration of the containment is unlikely even if hit, and that even if penetration occurred, it would not reach the reactor vessel.

Security Assessment

Without access to classified information, it is not possible to convincingly assess the security of the reactor sites. Even with such information, for example on the exact character of the DBT, nothing definitive can be concluded. For one reason, no one can really know how likely is a "beyond a DBT threat." Nevertheless, a few comments can be made.

In 2006, the GAO found that "the process NRC used to revise the DBT for nuclear power plants in April 2003 was generally logical and well defined. ... [T]he NRC threat assessment staff developed and used a comprehensive screening tool to analyze intelligence information and evaluate particular terrorist capabilities, or 'adversary characteristics,' for inclusion in the DBT. ... [The NRC Commission] produced a revised DBT that generally but not always corresponded to the original recommendations of the threat assessment staff."[71]

There were troubling aspects, however, to the GAO findings. With respect to the size of a car or truck bomb that could be used in the DBT, the Nuclear Energy Institute (NEI), representing the nuclear industry, argued for a less destructive bomb than initially assumed by the NRC staff on three grounds: "the low probability of a bomb the size proposed by the NRC; the likelihood that federal authorities or local law enforcement would detect a large vehicle bomb; and the inability of some sites to protect against the size of the vehicle bomb proposed by the NRC because of insufficient land for installation of vehicle barrier systems at a necessary distance."[72] This last reason especially appears the most jarring. In the event, the NRC staff did reduce the size of vehicle bomb assumed.

With respect to weapons, the Nuclear Energy Institute (NEI) argued against the inclusion of several weapons suggested by the NRC staff, and again it is the reasons

[71] U.S. Government Accountability Office, "Nuclear Power Plants: Efforts Made to Upgrade Security, but the Nuclear Regulatory Commission's Design Basis Threat Process Should Be Improved, GAO-06-388, March 2006, pp. 5-6.

[72] Ibid, p. 20.

forwarded by NEI that appear the most troubling. For example, the NEI wrote that one particular weapon recommended by the NRC staff "would render the ballistic shielding used at nuclear power plants obsolete, and that another proposed weapon would initially cost $1 million to $7 million per site to defend against, with annual recurring costs of up to $2 million." Partly in response to the NEI, the NRC staff did remove some weapons from the DBT, though not one at least which the NEI had objected to – and the NRC Commissioners later voted to remove that particular weapon.[73] The Program on Government Oversight (POGO) has argued that this weapon likely was the rocket-propelled grenade.[74] How much the NRC staff and Commissioners were swayed by the industry objections is not known. But what is most puzzling is that the NEI objected to the draft DBT partly on apparently relatively trivial economic grounds. Given that a typical nuclear reactor in the U.S. spends about $200 million per year in operating costs, the recurring $2 million per year cited by the NEI looks negligible.

Critics have pointed out that the threat used by the Department of Energy for its nuclear sites apparently includes three times the number of attackers in the NRC DBT.[75] This may be explained by the more urgent need to protect weapon-usable material at the sites from theft or actual use of an improvised nuclear explosive at the sites by terrorists. Also theft of nuclear material would require terrorists to both enter and leave the protected sites. It would appear that the effective design basis threats used by the NRC for facilities under its responsibility, which are using so-called Category 1 material (notably plutonium and highly enriched uranium), are not that different from the threats assumed by the Department of Energy.

The NRC staff told GAO that the NRC did not make changes to the draft DBT based solely on industry views. But, as noted by the GAO, "the process used to obtain feedback from the nuclear industry created the opportunity for, and appearance

---

[73] Ibid, pp. 20-21.

[74] Danielle Brian, Testimony before the House Subcommittee on National Security, Emerging Threats and International Relations, "Nuclear Security: Has the NRC Strengthened Facility Standards Since 9/11," April 4, 2006.

[75] Ibid. The DOE threat assessment is now under some flux. It may be that the 2005 DBT of the Department of Energy, which Danielle Brian of POGO referred to on the number of attackers, was never fully implemented. The DOE has now replaced its DBT with a "graded security protection" plan: "DOE Adopts New 'Graded' Terrorist Protection Policy," George Lobsenz, *Energy Daily*, August 26, 2008.

of, industry influence on the threat assessment regarding the characteristics of an attack." NRC officials assured the GAO that in considering future changes to the DBT, "NRC plans to ensure the initial separation of intelligence analysis from interaction with stakeholders."[76]

With respect to the FOF inspections and power-plant security arrangements, the GAO in its 2006 assessment, "saw a clear connection between the changes in the DBT and the plants' recent security enhancements. The plants' response to the revised DBT and other NRC orders following the September 11 terrorist attacks has been substantial ... Nevertheless, because the plants essentially designed their security to defend against the DBT outlined by NRC, their capability to defend against an attack is essentially limited to how similar such an attack would be to the DBT."[77] It is troubling that even with respect to the DBT, there were evidently three serious failures during the 2009 FOF exercises, which led to complete target set damage or destruction.[78]

Questions on the quality of the security personnel at the nuclear power plants have also been raised. In 2002, the Project on Government Oversight (POGO), in interviews with nuclear power plant guards, noted several disturbing concerns raised by the guards interviewed – that they were under trained, under equipped, and under paid.[79] After review, the NRC took various actions to improve security guard performance, including restricting security officer work hours and establishing new security force training and qualification requirements.[80] More recently, further concerns about guard fatigue were raised. In September 2007, a TV reporter presented the NRC with video evidence that showed a number of security officers at the Exelon's Peach Bottom station in Pennsylvania asleep in the site "ready room" (where security officers not on active patrol or observation post are stationed, ready to respond if called upon). This led to

---

[76] U.S. Government Accountability Office, "Nuclear Power Plants: Efforts Made to Upgrade Security, but the Nuclear Regulatory Commission's Design Basis Threat Process Should Be Improved," GAO-06-388, March 2006, pp. 21-22.

[77] Ibid, p. 42.

[78] Nuclear Regulatory Commission, *Report to Congress on the Security Inspection Program for Commercial Power Reactor and Category I Fuel Cycle Facilities: Results and Status Update*, Annual Report for Calendar Year 2009, p. 9.

[79] Project on Government Oversight (POGO), *Nuclear Power Plant Security: Voices from Inside the Fences*, Revised, October 2, 2002.

[80] Mark Holt and Anthony Andrews, *Nuclear Power Plant Security and Vulnerabilities*, 2010, p. 10.

Exelon severing relations with its security contractor, Wackenhut, and to the NRC issuing a security bulletin in December 2007 requiring licensees "to gather information on administrative and management controls and any other actions taken to address inattentiveness."[81]

Future Nuclear Power Plants

It may be that a massive release of radioactivity to the environment from a nuclear power plant, either through a failure of safety measures or through terrorist action, is an improbable event. But the consequences of such a release would be so devastating that the question should be asked whether future nuclear designs could render a massive release of radioactivity still more improbable – even, for example, if a terrorist group was able to take charge of a reactor site or to contrive to crash an airplane into the power plant or to attack it with precision-guided weapons.

The question is important because increasing the security at power plant sites, say by adding more security guards with more weapons, carries its own risks. Scott Sagan has pointed this out in a 2005 article. By illustration, Sagan notes that expanding the guard force could also increase the insider threat, could lead to social shirking of responsibilities by the guards, and could give a false sense of assurance, leading to more reckless behavior.[82]

The strongest defense to a catastrophic terrorist attack is to make the nuclear reactor sites as inherently safe as possible. While complete "inherent" safety against all possible pathways that could release radioactivity to the environment might not be practically achievable, it is conceivable such a goal could be approached. The goal has been stated thus by two nuclear experts, then at Oak Ridge National Laboratory:[83]

---

[81] Nuclear Regulatory Commission, *Report to Congress, 2008*, p. 6. Steven Mufson, "Video of Sleeping Guards Shakes Nuclear Industry," *Washington Post*, January 4, 2008.

[82] Scott Sagan, "The Problem of Redundancy: Why More Nuclear Security Forces May Produce Less Nuclear Security," *Risk Analysis*, Vol. 24, No. 4, 2004.

[83] Charles Forsberg and Thomas Kress, "Underground Reactor Containments: An Option for the Future?" 2nd International Topical Meeting on Advanced Reactor Safety, paper No. 159, American Nuclear Society, June 1-4, 1997.

> Nuclear power plants should be designed to ensure that the consequences of the worst-case accidents [or deliberate attacks] will be of only limited local concern. The prevention of large-scale release of radionuclides shall not depend upon plant operation and maintenance practice nor on the relative reliability of active safety systems and components.

For example, though spent fuel pools are generally not protected by a containment dome and in this sense more vulnerable than the reactor to attacks from the ground or air, the way in which the pools are managed could greatly affect the risks of large releases of radioactivity in the event of loss of cooling. Thus, a study by independent scientists in 2003 showed that with dense packing of the spent fuel, a loss of water coolant could potentially lead to a propagating zirconium fire (zirconium being the material commonly used in cladding the fuel rods) and a large radioactive release to the environment.[84] A National Academy of Sciences study, released in 2005, supported this analysis. Both analyses, however, suggested ways to manage the spent fuel pools (for example, by more rapid removal of spent fuel to dry-cask storage, or, in the NAS study, by careful interspersing of hotter and cooler spent fuel), which would make a zirconium fire much less likely.[85]

With respect to reactor technologies, there may also be ways to achieve a formidable degree of inherent safety. For example, the modular pebble bed reactor in which the pebbles are not expected to melt even if the coolant is completely and permanently lost, could look attractive on such safety and security grounds, though the possibility and consequence of graphite fires would have to be further studied. Also many of the array of small reactors now being designed appear to have features of intrinsic safety.

While it is beyond the scope of this chapter to discuss the feasibility and economics of achieving the goal of inherent safety, in general, it is worth noting one possibility that Forsberg, Kress, and others have highlighted – underground siting of nuclear reactors. The argument is that underground containments can provide very strong resis-

---

[84] Robert Alvarez et al. "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security*, Volume 11, 2003, pp. 1-51, and "Response by the Authors to the NRC Review of 'Reducing the Hazards ...'," *Science & Global Security*, Volume 11, 2003, pp. 213-223.

[85]National Research Council, Board on Radioactive Waste Management, *Safety and Security of Commercial Spent Fuel Storage*, Public Report, National Academies Press, Washington, D.C., 2005.

tance to assaults and accidents. As noted by Forsberg and Kress, "high technology weapons or some internal accidents can cause existing ... containments to fail, but only very high energy releases can move large inertial masses associated with underground containments." It certainly would appear to be the case that underground containment would protect power plants from aircraft crashes and attacks off site by rocket propelled grenades and the like. Whether the underground siting could largely contain releases from a meltdown of a reactor seems less clear, but that too may be possible. And naturally, the vulnerability of underground-sited reactors to extreme seismic events would have to be carefully assessed.

Conclusion

Security at nuclear power plants appears to have improved since 9/11. The Design Basis Threat has been increased some, and the force on force exercises by the NRC, done once every eight years before 9/11, are now being done every three years. However, questions remain whether the DBT is yet realistic enough to capture plausible threats by terrorist groups, and whether the DBT and associated reactor security operations have been adjusted to accommodate industry concerns with cost.

Whatever the DBT, there will always be the possibility of a beyond-DBT attack on a reactor. This suggests the value of the nuclear industry seeking reactor designs and operational procedures that are more inherently safe than the current systems.

Chapter 6

FUTURE URANIUM SUPPLIES FOR U.S. NUCLEAR REACTORS

by Ivan Oelrich

A possible constraint on future nuclear-electricity production could be limits in the supply of uranium fuel. Complex calculations of future uranium demand and supply really boil down to a single central question: Given that nuclear reactors take a decade to build and can operate for 60 years, should a decision today about building a nuclear reactor take into account the possibility that its productive lifetime will be cut short by lack of fuel? The answer today is "no." Well-characterized reserves of uranium are large enough to power all existing and currently planned reactors to the ends of their lives. The history of uranium discovery strongly suggests that the answer will not change for at least a few decades into the future.

Uranium was discovered in 1789, and for the next one and a half centuries had only minor practical applications, such as a pottery glaze and a glass coloring agent.[86] Consequently, little effort was put into prospecting for ore deposits. Unsurprisingly, with no one looking, little of the element was found. Uranium deposits were assumed to be geological oddities, occurring in useful concentrations at very few sites around the globe. (At the end of World War II, the United States thought it might be able to maintain a nuclear weapons monopoly by cornering the world's uranium market.) It has turned out, however, that uranium is fairly common and widespread; even with robust growth in nuclear power, the United States and the world have many decades' supply of uranium available.

The importance of uranium changed dramatically and irrevocably with the discovery of nuclear fission. In the winter of 1938-9, German scientists found that the newly discovered neutron could split a uranium atom with an accompanying release of fantastic amounts of energy. When scientists also found that, when the uranium atom broke apart, it emitted additional neutrons that could themselves split even more atoms,

---

[86] Tom Zoelllner, *Uranium: War, energy, and the rock that shaped the world*, Viking, New York, 2009, p. 17.

the possibility of a chain reaction was obvious. A runaway chain reaction would result in an explosion while a controlled chain reaction might provide a constant source of power that could be harnessed. With World War II looming, fission's application to a new super-weapon could not be ignored and President Roosevelt established the Manhattan Project to develop nuclear weapons. The first nuclear weapon used in war, exploded over Hiroshima, Japan, was powered by uranium.

The wartime Manhattan Project also included development of the first nuclear reactors. They were used to produce plutonium for bombs but their peaceful applications were clear from the beginning. While the United States built the first reactor to produce electricity, the Experimental Breeder Reactor in Idaho, it was little more than a stunt using a research reactor to power four large light bulbs (the reactor is now a National Historic Landmark).[87] In 1954, the Soviet Union built the first reactor that fed electricity into a power grid, providing about 5 megawatts (MW) to the city of Obninsk.[88] The British built the first of what would today be recognized as a commercial nuclear reactor, the 50 MW Calder Hall 1, which began operation in 1957.[89] The United States soon followed in December 1957 with the Shippingport reactor. Nuclear power grew steadily from that point until the Chernobyl accident when new reactor construction almost stopped for two decades except in some Asian countries. Today, the world's approximately 440 commercial nuclear reactors have a electrical generating capacity of about 373,000 megawatts and produce about 2.6 trillion kilowatt-hours of energy per year, requiring 68,000 tons of uranium per year.[90]

Predicting future U.S. uranium availability requires a comparison of demand and supply. Uranium demand is discussed first. Demand must address both the demand for nuclear-generated electricity and the efficiency with which uranium is used to produce that electricity. Supply calculation must consider established and estimated reserves of uranium ores and how estimates of resources can expand as greater effort, and

---

87 "EBR-1 Factsheet," Idaho National Laboratory, http://www.inl.gov/factsheets/ebr-1.pdf

88 "Nuclear Power in Russia," World Nuclear Association, updated March 2011, http://www.world-nuclear.org/info/inf45.html

89 Nuclear Energy Agency, *Forty Years of Uranium Resources, Production and Demand in Perspective*, OECD, Paris, 2006, p. 2.

90 Nuclear Energy Agency/International Atomic Energy Agency, *Uranium 2009: Resources, Production and Demand*, Paris, 2010, p. 59.

of course money, is devoted to uranium extraction. The chapter ends with a discussion of uranium enrichment demand and capacity in the coming decades.

Demand

Early in the nuclear era, uranium demand was dominated by the need for highly enriched uranium (HEU) for nuclear weapons production but, with the end of the Cold War, the United States stopped HEU production for nuclear weapons in 1992. Thus, today, uranium requirements are essentially determined by commercial nuclear power plants' needs and those depend, in turn, on the amount of energy produced by nuclear reactors and the efficiency with which the reactors use their uranium fuel. (Research reactors and naval propulsion reactors, while significant in number and sometimes presenting real proliferation risks, are small and have little effect on global uranium consumption.)

Predictions of uranium consumption begin with predictions of reactor operation and production. Nuclear reactors take years to plan and build, so predictions can be reliably made about installed capacity of nuclear power plants a decade into the future. Reactors, once built, operate for 60 years and perhaps longer, so current reactor capacity provides a reliable prediction of baseline or minimum installed capacity for a few decades into the future. In the case of the United States, there are few new reactor construction projects underway (although many applications for new reactors are under review by the Nuclear Regulatory Commission). Thus, existing reactors will make up the U.S. inventory for at least the next 20 years. Uranium use depends, not on installed reactor capacity but on actual electricity production, but reactors are expensive so utilities try to operate them as close to maximum capacity as possible. With greater experience, reliability has improved to the point that U.S. reactors now typically operate at close to 90 percent or greater capacity, thus, maximum capacity is a good predictor of actual use.

The greatest uncertainty in future reactor capacity lies in the number of reactors that will come online a decade or more into the future. Future construction plans depend on overall demand for electricity, concerns about atmospheric carbon dioxide, levels of government support, the cost of capital, and the availability of inexpensive natural gas; none of these can be reliably predicted. (Moreover, predicting future U.S. capacity is not enough; uranium is a globally traded commodity, so U.S. operators must compete for uranium supplies in a global market, which means that global nuclear reactor capacity and consumption affects uranium availability in the United States.)

Aside from one small dip in 1998, the total capacity of U.S. nuclear reactors has gone up every year since the beginning of the nuclear age. Typically, predictions of future nuclear power capacity are based on an assumption of some constant growth in electricity consumption and generation, usually 1.5 to 2.0 percent a year, and further based on the assumption that nuclear power will continue to provide at least as large a fraction of overall capacity as today but with the fraction most likely increasing. However, from the beginning of the nuclear age, almost all predictions of future generating capacity have been too high; thus, current predictions should be viewed with some caution.[91] In the past, overestimates were due to overly optimistic estimates of social and political acceptance and of the cost of producing nuclear electricity. For predictions made today, the dominating assumption is extrapolation of electricity demand. The often cited 2003 MIT study, *The Future of Nuclear Power* assumed, for example, that U.S. electricity consumption would almost double over the next 40 years but also showed that other countries with the equivalent quality of life, as measured by the UN Human Development Index, use far less electricity.[92] Australia uses two thirds as much electricity per person as Americans while rich European countries, such as Germany, Britain, and the Netherlands use one half as much electricity per person.[93] Simple extrapolation of power demand ignores ever-increasing conservation pressures and potential in the developed world and in the United States, in particular.

Some advocates of nuclear power today talk about a "nuclear renaissance," resulting from a recovery after the long post-Chernobyl hiatus in reactor construction and from increasing concerns about global warming and desires for low-carbon energy but even this enthusiasm is dampening. For example, the 2003 MIT study predicted, as a lower bound, that by 2050 the United States would have 386 gigawatts (or GW, a gigawatt is a billion watts) of installed nuclear capacity, but the MIT study group's 2009 update noted that no new reactor construction had begun in the United States. Thus, the authors saw that even that lower bound projection was overly optimistic. (Since then, some new construction has begun at the Vogtle site in Georgia.)

---

[91] *Forty Years*, op. cit., p 27.

[92] John Deutch and Ernest Moniz, co-chairs, *The Future of Nuclear Power, an interdisciplinary study*, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2003.

[93] Ibid., p. 109.

The global picture is much different from that in the United States alone. At the end of 2010, there were 441 civilian power reactors operating across the world with 58 more under construction.[94] With reactor lifetimes now being extended to 50-60 years, new construction will outpace retirements for at least several years and the number of reactors will certainly increase. The same study cited above that suggests the potential for energy conservation in the United States also shows that there seems to be an increase in quality of life with electricity use above about two to three thousand kilowatt hours of electricity use per person per year. The majority of the world's population, including China and India, is below this level and will want to reach it over the next half century. Therefore, regardless of conservation in the rich countries, global electricity use will continue to increase and the fraction of that produced by nuclear in developing countries can only grow because it is such a small fraction today. This means that the United States, independent of its own needs, will be competing in a global market of ever increasing demand.

Today, about 20 percent of total U.S. electric generating capacity comes from nuclear plants with 101 GW of installed nuclear generating capacity,[95] which produced 806 terawatt-hours of electric energy (a terawatt is a trillion watts),[96] implying an industry average production of 91 percent of capacity. This energy production in the United States consumed the equivalent of 16,424 tons of uranium metal (in 2008). The Department of Energy (DOE) reports that its "high" consumption estimate in 2030 is about 23,000 tons. Extrapolating to mid-century produces a total requirement between now and then of 920,000 tons of uranium metal. The "low" estimate of the MIT study is about twice this rate of growth, which, added to the existing baseline, results in total requirements by mid-century of 1200 thousand tons of uranium metal.

Supply

Global uranium reserves are reported every second year by the International Atomic Energy Agency (IAEA) in a report called *Uranium [the year of publication]: Resources, Production, and Demand* and, because of its cover, referred to informally as the *Red*

---

[94] See World Nuclear Association, http://www.world-nuclear.org/info/reactors.html, accessed November 2010.

[95] *Uranium 2009,* op. cit., p. 60.

[96] Ibid, p. 62.

Book. While the *Red Book* is considered authoritative, it depends on voluntary reporting by participating nations. Resources are described by level of confidence in the quantity of the deposit, the cost of extraction, and by region.

Until the ore is actually taken out of the ground and processed, there is some uncertainty about its uranium content. The *Red Book* distinguishes among various levels of confidence in reserves. The highest confidence deposits are *Known Conventional Resources* (KCR), usually comprising deposits in existing or planned mines. Next is *Reasonably Assured Resources* (RAR), which are deposits that are not fully characterized but in which there is high confidence. Most reports of uranium "reserves" lump KCR and RAR together into *Identified Resources*. Beyond this are more speculative estimates, down to estimates based, not on actual prospecting data, but on wide-scale geological surveys that identify geologic formations of a type that have elsewhere contained uranium deposits and are thus assumed to be likely candidates for future resources.

While the United States consumes 17 percent of the world's uranium production, it has only seven percent of the world's reserves and cannot, under free market conditions, be self-sufficient in uranium but this should not be a security concern for several reasons. A significant fraction of the world's petroleum is concentrated in the politically uncertain Middle East; in comparison, uranium is widely distributed around the globe. Some of the largest reserves are held by America's closest allies, Canada and Australia. Other large reserves are widely dispersed, such as in southern Africa and central Asia, so are unlikely to be disrupted simultaneously. Finally, the cost of uranium as fuel is, unlike coal or natural gas, a small slice of the total cost of producing electricity; in addition, the energy density of uranium fuel is thousands of times higher than coal, making the volume of the fuel low. These two factors together mean that stockpiling even years of supply is economically and strategically feasible.

The world's largest uranium reserves and the largest producers are shown in Table 1. Note that the countries with the largest reserves are not always the largest producers. Australia, for example, has the largest proven reserves but did not start to rise as a big producer of uranium until 1980. (Australia does not have commercial nuclear plants.) Counting from the beginning of the nuclear age, the United States, Canada, and the Soviet Union were the largest cumulative producers of uranium. (This was, at least in part, a reflection of the Cold War and its demand for a huge arsenal of nuclear weapons.) Since the mid-1970s, uranium became less of a strategic/military commodity and more of a normal commercial commodity and several other countries expanded uranium mining operations. While the United States still has large reserves, other countries have developed ore deposits that are cheaper to extract so the relative current economic attractiveness of U.S. extraction has declined. The United States' production peaked in 1980. Canada, while not having the largest reserves, has some of the richest ore deposits in the world and the cheapest to extract so has remained the world's largest producer until 2008. While Russia still is a major producer, most Soviet production and reserves were in Kazakhstan. In just the last few years, Kazakhstan has invested heavily in mining with a resultant surge in production. In 2009, it surpassed Canada as the world's largest producer.[97]

The world's proven reserves of uranium have been increasing since the 1980s. Although nuclear reactors are consuming uranium constantly and over two million tons of uranium have been extracted since 1945,[98] reserves are increasing for two reasons: first, continuing prospecting has expanded the number of sites where uranium is known to be; and, second, technical developments have allowed better extraction of uranium, for example, by *in situ* solvent pumping methods and, in the future, bacterial concentration, in addition to traditional mining operations.

For reserves, absolute numbers are less significant than years of supply. By this measure, reserves have held roughly constant for the past quarter century with about 45 years of supply identified in proven and probable reserves. This number and its stability are not a coincidence. Once forty or so years of reserves have been identified, there is little economic incentive to invest money in finding new sources; consequently, prospecting slows, and the discovery of new deposits slows proportionately until reserves fall below the forty year threshold. Similarly, as long as high-grade ores that are cheap to extract are available, there is little incentive to invest in more advanced technology to extract uranium from poorer quality ores.

The cost of extraction is integral to estimates of reserves. As the market is willing to pay more for extraction, the number of ore deposits that are exploitable increases. Thus, any estimate of reserves cannot simply be a cited amount but an amount extractable at a specified cost. (With prices high enough, uranium could theoretically be extracted

---

[97] World Nuclear Association, "Uranium Mining," updated April 2011, http://www.world-nuclear.org/info/inf23.html.

[98] *Forty Years,* p.13,

from seawater, increasing reserves by factors of hundreds or thousands.)[99] Reserves are today typically reported for cases for which the uranium can be extracted for less than \$130/kg of uranium metal. (The standard 130 number comes about because the United States once reported reserves in terms of dollars per pound of uranium oxide; thus \$130/ kg metal is equivalent to the \$50/lb U_3O_8 breakpoint.)

Currently identified reserves extractable at \$130/kg are 5.4 million tons of uranium metal but, if ores available at <\$260/kg are included, the amount more than doubles to 11.7 million tons. More speculative resources total an additional ten million tons.[100] The *Red Book* suggests that data about ongoing mining operations may be considered proprietary so may be under-reported. Reserves of expensive uranium may be underestimated relative to cheaper reserves because there is no incentive to prospect for expensive deposits when more than adequate cheaper deposits are known. In the second half of the century, as the cheapest deposits are exhausted, more attention will be given to what are today marginal ores and these reserves will increase. And some nations do not even report speculative resources; thus, those are almost certainly underestimated. Over the past quarter century, uranium prices have hovered around \$50/kg metal and over the last few years have approached \$100/kg, so estimates of resources available at \$130/kg include uranium at prices higher than today's. Higher uranium costs are, however, less significant than for other types of electricity-generating fuel because the uranium itself constitutes only about 4 percent of the cost of producing nuclear electricity. (Nuclear costs are dominated by the capital costs of the power plant). Thus, if prices actually did reach \$130/kg, nuclear electricity costs would only go up by a percent or two.

In 2010, total uranium production was 53,660tons of metal.[101] Thus, at current extraction rates, existing identified < \$130/kg reserves would last 112 years. Current production does not meet current use, however. The United States consumes about 17 percent of the world's uranium, but about half of that is provided by a U.S.-Russian program called Megatons-to-Megawatts, in which 500 tons of highly-enriched uranium from old Soviet nuclear weapons are diluted and consumed in U.S.

---

[99] H. Nobukawa, "Development of a Floating Type System for Uranium Extraction from Sea Water Using Sea Current and Wave Power," in *Proceedings of the 4th International Offshore and Polar Engineering Conference* (Osaka, Japan: 10-15 April 1994), pp. 294-300.

[100] *Uranium 2009*, p. 10.

[101] "Uranium Mining," op cit.

reactors, providing the equivalent of 100,000 tons of natural uranium. This residual inventory left over from the Cold War will be consumed soon after the program ends in 2013. Adjusting for the end of this outside source, current known reserves will meet current demand for only another 92 years. Of course, while future consumption is unknown, it will increase, so current identified reserves will be consumed sometime before then. Using the *Red Book* "high" estimates for growth, currently identified reserves will last 42 years—consistent with the long-term stability of around forty years of reserves—and using its "low" growth estimate they will last 57 years. All of these numbers should be roughly doubled if currently identified and well-characterized <$260/kg reserves are included.

Enrichment

Most chemical elements have more than one isotope, that is, atoms that are chemically virtually identical but have slightly different weights or mass. Most of the mass of the atom is in the nucleus and differences in mass come about because the nuclei have different numbers of neutrons. While the number of neutrons has almost no effect on the normal chemistry of an atom, it has a profound effect on the nuclear properties. Uranium has two important isotopes, U-235 and U-238, where the number indicates the total number of protons and neutrons in the nucleus.

It is the lighter U-235 that can be easily split by neutrons and sustain a chain reaction, powering both nuclear reactors and nuclear weapons. But natural uranium contains only 0.72 percent U-235; the 99.28 percent remainder is U-238. (Trace amounts of another isotope, U-234, occur in natural uranium but are not directly important to nuclear power production.) Some reactors, using special materials, such as heavy water (that is water containing the stable heavy isotope of hydrogen called deuterium), can use natural uranium as fuel. One example is the very successful CANDU, or CANadian Deuterium Uranium reactor. However, the great majority of the world's existing and planned nuclear reactors use and will use normal, or light, water and for these reactors the fraction of U-235 must be increased above the natural concentrations. This process of increasing the concentration of U-235 is called *enrichment*. The amount of enrichment capacity required is closely proportional to the energy produced by light water reactors.

Because the chemical properties of different isotopes are virtually identical, some physical process that exploits the small difference in the mass must be used to separate them. Although uranium is the heaviest natural element, it forms a compound with fluorine, uranium hexafluoride or UF_6, which is a gas at only slightly elevated temperatures. Coincidentally, fluorine has only one stable isotope, F-19, so any difference in the mass of the UF_6 molecule has to be due to differences in the mass of the uranium. All commercial enrichment methods use uranium in this gaseous form of UF_6. The process of turning uranium metal or oxide into UF_6 is called *conversion*.

The first enrichment process to be used on a large scale was gaseous diffusion, developed during the Manhattan Project, which exploits the slightly faster diffusion through a metal mesh of the lighter UF_6 containing U-235. The first countries to develop nuclear weapons, the United States, Russia, Britain, France, and China all developed huge gaseous diffusion plants. Each stage achieves only very slight enrichment so many stages are needed and the gas must be recompressed each time, consuming huge quantities of electricity. (It is no coincidence that the first American gaseous diffusion plants were built in the heart of the Tennessee Valley Authority's hydroelectric production area.)

In theory, centrifuges are more efficient at separating uranium isotopes, requiring only a twentieth or so as much electricity. The idea of using centrifuges predates the Manhattan Project but, to be effective, the centrifuges must spin at extremely high speed and technical limitations of the needed high-strength materials and high-speed bearings made early centrifuges impractical. These problems were slowly overcome so that, by the 1960s, centrifuges were far and away the preferred enrichment method. While some old diffusion plants are still in operation, they are facing retirement and all currently planned industrial-scale enrichment plants will use centrifuges.

The degree of enrichment of uranium is measured by Separative Work Units, usually abbreviated SWUs. The separative capacity is the degree of enrichment of a given amount of material, so total separative "work" is typically measured by a SWU of enrichment on one kilogram of material, or a kg-SWU. (The "kg" is often incorrectly dropped in much writing and reported as simply SWU. Some older British and American texts use pound-SWUs. The output of entire enrichment plants is sometimes reported in ton-SWUs.)

A typical nuclear power plant will have an electrical output of a gigawatt. With an efficiency of converting heat to electricity of one third, the plant will produce 3 GW of heat and, over the course of a year, consume about 25 tons of uranium fuel enriched to about 4 percent U-235. Starting with natural uranium, this typical power plant requires about 100,000 to 120,000 kg-SWUs per year. (As one fraction of uranium becomes more concentrated in U-235, obviously the remainder is less concentrated; this is called "depleted uranium." The depleted remainder from the enrichment process, call the tails, typically contains 0.2-0.25 percent U-235. How much U-235 is left in the tails depends on a cost calculation determined by a tradeoff between the cost of separation and the cost of fresh uranium.)

The world's enrichment capacity is concentrated in just a few countries. Russia is the largest, with a 25 million kg-SWU/yr capacity. Recall that Russia will, for a few more years, continue selling off fuel made by dilution of weapons-grade uranium, which has the same effect as enrichment capacity. France's Areva/Eurodif can produce 11 million kg-SWU and the Anglo-German-Dutch consortium Urenco can produce another 11 million.

The enrichment capacity is changing rapidly in the United States. The United States currently produces about 11 million kg-SWU/yr. Based on a need of 120 thousand kg-SWU/yr/GW, the United States requires a little over 12 million kg-SWU/yr. The country now depends on an outdated gaseous diffusion plant in Paducah, Kentucky, a legacy of the Cold War enrichment program that originally produced highly-enriched uranium (HEU) for weapons. The Paducah plant is facing retirement and the supply of diluted Russian nuclear weapon uranium is about to end. To compensate, two modern gas centrifuge plants are planned. One, to be built by the United States Enrichment Corporation (USEC), will be near Paducah and use advanced centrifuges developed at Oak Ridge National Laboratory. It will have about four million kg-SWU/yr capacity. The European consortium, URENCO, is building a centrifuge facility in New Mexico that will add another six million kg-SWU/yr.[102] A pilot plant facility that uses finely-tuned lasers to separate the isotopes of uranium is under construction in Wilmington, North Carolina, but the process is considered proprietary and few details are available.

In general, there should be little concern about limitations of enrichment capacity because, by all measures, whether capital requirements, construction time, or technical, environmental, and political hurdles, the challenges facing nuclear power plants are far more daunting that those facing enrichment plants. In short, the United States and the world can apparently install enrichment capacity faster than it can install reactor capacity; thus, enrichment should be able to keep up with demand.

---

[102] World Nuclear Association, "Uranium Enrichment," October 2010, http://www.world-nuclear.org/info/inf28.html

Recall that natural uranium is only 0.7 percent U-235. Only about 70 percent of that is extracted, the remainder is left in the "tails" because the cost of further extraction exceeds the cost of starting with fresh natural uranium. If improvements in enrichment technology, for example, laser enrichment, could substantially reduce the cost of enrichment, then more U-235 would be extracted from any given amount of natural uranium. This could significantly, if not dramatically, increase the world's effective supply of U-235.

Conclusion

Predictions of near term uranium demand are quite precise. Growth rates over the coming decades are, in contrast, highly uncertain. Unknown uranium resources are, obviously, unknown so upper bounds on availability are completely uncertain. But well-characterized resources provide a floor on available nuclear fuel, and these resources are large. Even allowing for robust growth in nuclear-electric power generation and using fairly conservative assumptions about current and future reserves, decisions about building nuclear reactors should not today be constrained by concerns about fuel availability. The long-term fuel situation will be constantly reevaluated but, for decades to come, uranium availability will most likely not be the factor limiting nuclear growth.

Table 1. Major Producers and Known Uranium Reserves

2008 Resources and Production	Identified Resources at < $130/kg (1000s tons metal)	Production (tons metal/yr)
Australia	1673	8433
Brazil	279	330
Canada	485	9000
Kazakhstan	652	8512
Namibia	284	4400
Niger	273	3032
Russia	480	3521
South Africa	296	565
United States	207	1492

Chapter 7

PROSPECTS FOR A PLUTONIUM ECONOMY IN THE UNITED STATES

by Ivan Oelrich

Plutonium is an element not found in nature, but a typical nuclear power reactor produces hundreds of kilograms of the material each year. Plutonium has the potential to power nuclear reactors by itself, thereby increasing, in theory, the energy extractable from uranium by a factor of about a hundred, extending uranium reserves, perhaps by a thousand years. Many attempts have been made to exploit this theoretical potential, but practical limitations of engineering and economics have thwarted widespread application. As long as adequate supplies of cheap uranium are available, as discussed in the previous chapter, which will be at least many decades and probably until the end of the century, plutonium will have to wait. Plutonium separation also presents proliferation dangers because it can be used to power nuclear weapons as well as reactors.

Plutonium is one of the most dangerous long-term components of nuclear waste. Schemes for separating plutonium from waste and treating it have been proposed, but have not proven economical compared to geological disposal or even century-long storage in dry casks until permanent storage can be arranged.

Plutonium and Commercial Nuclear Power

Through a series of radioactive decays, the uranium-238 (U-238) in the fuel of a reactor transforms within a few days into plutonium, or Pu-239, which *is* fissile, and because it has a half-life of about 24,000 years, it does not appreciably decay further. Plutonium and other artificial elements beyond the heaviest natural element, uranium, are called *transuranics*. Because of its ability to transform into a fissile atom, U-238 is said to be, not fissile, but *fertile*.

The production of fissile material from fertile material is called *breeding* and reactors specifically designed to produce plutonium or other artificial fissile materials are *breeders*. Through this indirect mechanism, the latent energy in U-238 can be extracted. Because all commercial reactors powered by uranium-235 (U-235) have even more U-238 in their fuel, the sea of neutrons in the reactor will convert some U-238 to plutonium inside the reactor and some will be consumed right there in the reactor where it is produced, a process sometimes called *in situ* or internal breeding. In this way, a third of so of the energy in a typical reactor is derived from plutonium created from the U-238, not from the U-235.

When commercial uranium fuel is exhausted, it is approximately one percent plutonium, with the concentration varying by type of fuel and reactor. The United States currently has about 62,000 tons of commercial reactor fuel waste and is producing about 2300 tons a year.[103] At one percent, that translates into 620 tons of plutonium locked up in used fuel elements. Most of that is the useful isotope Pu-239, which contains, kilogram for kilogram, about as much energy as U-235 which means that used reactor fuel actually has a higher fissile energy potential than natural uranium. Fully exploiting the potential of plutonium production requires, however, that the plutonium be separated from the irradiated nuclear fuel. While different isotopes of an element are virtually identical chemically, making their separation difficult, uranium and plutonium are different elements with different chemical properties so they can be separated by relatively simple chemical means.

Separating Plutonium

The first techniques for producing and separating plutonium were developed in the Manhattan Project to make plutonium for nuclear weapons. The Manhattan Project technique, called PUREX, for Plutonium-URanium Extraction,[104] still has variants in use today. Chemically separating the components, including plutonium, from used nuclear fuel is called *reprocessing*. In the PUREX process, the used fuel is dissolved in nitric acid and then an organic solvent is used to extract the uranium and plutonium and

---

[103] Nuclear Energy Institute, *Nuclear Waste: Amounts and On-Site Storage*, undated, http://www.nei.org/resourcesandstats/nuclear_statistics/nuclearwasteamountsandonsitestorage/, accessed 10 December 2010.

[104] M. S. Gerber, *A Brief History of the PUREX and UO_3 Facilities*, U.S. Department of Energy Office of Environmental Restoration and Waste Management, Novemeber 1993.

many other heavy, radioactive nuclei. By adjusting the chemical conditions of the solvent, the various components can be isolated by precipitating them one at a time from the solution.

Plutonium from a commercial nuclear reactor, while not ideal, can be used to make a nuclear bomb so variations on the PUREX process have been developed that do not isolate pure plutonium. Some of these schemes involve extracting the plutonium and uranium together so the concentration of plutonium is not high enough to make a bomb. The shortcoming of this approach is that it makes the plutonium, albeit impure, much easier to steal. Spent reactor fuel contains fission products, making it so intensely radioactive that the International Atomic Energy Agency describes it as "self-protecting," that is, potential unauthorized proliferators or terrorists would be killed by ionizing radiation before they could get very far with their booty. The plutonium/uranium mixture is far less radioactive and, once it is stolen, it can easily be run back through the old PUREX process and the pure plutonium extracted. Other schemes involve intentionally leaving in radioactive materials that are difficult to separate from plutonium but these typically do not meet the criteria of being self-protecting.[105]

Most U.S. plutonium was produced as part of the nuclear weapons program at reactors at Savannah River, South Carolina and Hanford, Washington, and then separated using the PUREX process.[106] The only commercial effort to separate plutonium from fuel took place at a facility at West Valley, New York. It operated from 1966 through 1972 and during that time processed 640 tons of fuel, on average about one fifth its design capacity. The facility caused significant environmental contamination that is estimated to cost about $4.5 billion to clean up.[107]

The French still operate a large separation facility at La Hague that uses a PUREX process.[108] The British also have a large facility near Sellafield, called the

---

105 Jungmin Kang and Frank von Hippel, "Limited Proliferation-Resistance Benefits from Recycling Unseparated Trasnuranics and Lanthanides from Light-Water Reactor Spent Fuel," *Science and Global Security, 13*, pp-169-181, 2005.

106 *Plutonium: The First Fifty Years: United States plutonium production, acquisition, and utilization from 1944 through 1994*, United States Department of Energy, February 1996.

107 U.S. General Accountability Office, GAO-01-314, *Nuclear Waste: Agreement Among Agencies Responsible for the West Valley Site Is Critically Needed*, May 11, 2001, p. 2.

108 Mycle Schneider and Yves Marignac, *Research Report No. 4, International Panel on Fissile Materials, Spent Nuclear Fuel Reprocessing in France*, International Panel on Fissile Materials, April 2008.

Thermal Oxide Reprocessing Plant, or THORP, that uses the PUREX process,[109] but the facility was shut down after a major leak of radioactive material occurred in 2005. The plant will probably will not be reopened. Russia has a reprocessing facility at Mayak. Japan is struggling to open a large reprocessing facility at Rokkasho-mura. China and India also want commercial reprocessing facilities. However, the vast majority of countries that use commercial nuclear power do not reprocess spent fuel, and most of these countries do not use recycled plutonium fuel.

In some new approaches, called pyroprocessing, plutonium and the rest of the fuel are melted directly or dissolved in molten salt. Chemical or electrochemical processes then separate the plutonium. Some of these approaches are designed to make it inherently difficult to separate pure plutonium. Pyroprocessing has, however, not yet been demonstrated on commercial scales.

Plutonium as Reactor Fuel

The separated plutonium can be recycled through nuclear reactors, fissioned, and the energy converted into electricity. In the most common commercial power reactors, neutrons must be slowed down or *moderated* to increase their reactivity (and because the neutrons are in thermal equilibrium with the reactor material, these neutrons are called *thermal* neutrons). Most reactors use normal or "light" water as both a moderator and coolant (as opposed to "heavy" water made with a heavy isotope of hydrogen). Light Water Reactors (LWRs) cannot operate with natural uranium because the concentration of U-235 is too low; the concentration must be increased through enrichment to 3-5% U-235 for typical reactors. Plutonium can replace some of the U-235 so that plutonium-spiked uranium can be used as a fuel much like enriched uranium. The fuel is used in its ceramic-like oxide form, so the uranium/plutonium fuel is called MOX, or Mixed OXide, fuel.

Today, France, as mentioned above, reprocesses plutonium from LWRs and recycles it back through its LWRs, but there are severe limitations to this approach. The first is cost. When used fuel is removed from a reactor, it is intensely radioactive, making handling and reprocessing difficult and expensive. A 2005 study estimated reprocessing costs of $2000/kg of spent fuel, which would contain only about ten grams

---

[109] Martin Forwood, *Research Report No. 5, International Panel on Fissile Materials, The Legacy of Reprocessing in the United Kingdom,* International Panel on Fissile Materials, July 2008.

of plutonium.[110] Recent experience with severe delays and cost overruns at Japan's Rokkasho reprocessing plant suggest that technical advances will not dramatically reduce costs soon. Fresh uranium and the required enrichment together are significantly cheaper than extracting plutonium from used fuel and will most likely remain so for at least several decades and probably to the end of the century.

There are also fundamental physical limits on plutonium recycling. As the plutonium is passed back through the LWR, some is fissioned, but some simply absorbs a neutron without splitting thereby creating heavier isotopes of plutonium; for example, Pu-239 can be converted to Pu-240, and these isotopes are not readily fissioned in an LWR; indeed they can absorb neutrons and inhibit the operation of the reactor. Just as in the case of uranium, different isotopes of plutonium are chemically identical and cannot be easily separated. In practice, therefore, the plutonium is usually passed through an LWR only once because of this build up of heavier isotopes.[111] The nuclear waste products from MOX fuel must then be pulled from the recycling loop, and they are not significantly different than wastes from pure uranium fuel and must be disposed of in some manner, almost certainly in a deep geological repository. Reprocessing and recycling the plutonium from LWR fuel increases by only one sixth the amount of energy extracted from the uranium.

Special Plutonium Reactors

To fully exploit the energy potential of plutonium requires both reprocessing and a different type of nuclear reactor, one that can fission uranium plus all the isotopes of plutonium, as well as other artificial transuranic elements, such as americium, that are bothersome components of normal nuclear waste. Such a reactor depends on allowing the neutrons to react while they are still at high energy, that is, *fast neutrons*, hence these are called *fast reactors* (as opposed to LWRs, which use slow or thermal neutrons and are called *thermal reactors*). Fast neutrons can split most heavy atoms, including the heavier isotopes of plutonium that an LWR will not. Moreover, the fissioning of plutonium by fast neutrons produces more neutrons than other reactions do, making breeding most effective.

---

110 Steve Fetter and Frank von Hippel, "Is U.S. Reprocessing Worth the Risk?," *Arms Control Today*, September 2005, accessed 10 December 2010.

111 However, France has performed a twice reprocessing on some plutonium but prefers to reserve the once-recycled material for future fast neutron reactors if and when these become commercially available.

Fast reactors date back to the beginning of the nuclear age. The United States, Soviet Union, and now Russia, France, Germany, Japan, and Britain have experimented with fast reactors. (India has plans to develop them.) Global research and development on fast reactors is conservatively estimated to be at least $50 billion,[112] but no fast reactor has been commercially successful.[113] Fast reactors are inherently more complex than LWRs, and designers believe that any eventual fast reactor will be at least a quarter more expensive than a comparable LWR. Current fast reactors designs are cooled by liquid sodium, which is inflammable and can explode upon contact with water, raising additional safety questions.

The failure of fast reactor development explains existing reprocessing efforts. It is reasonable to ask why, if reprocessing is uneconomic and inappropriate for LWRs, France does it and Britain did until recently. Both programs go back decades. In the 1950s, Britain, France, and the United States were working toward a commercial reprocessing capability and, in parallel, fast breeder reactors that could fully exploit the plutonium produced. The French built the Rapsodie reactor, followed by the Phenix, which was reasonably successful as a demonstration but too small to be commercially viable. This was followed by the Superphenix, a 1.2 gigawatt reactor that was a technical and commercial failure. The British had a similar experience; the Dounreay Fast Reactor (DFR) was a reasonably successful small demonstration, but the scaled up version, the moderately-sized Prototype Fast Reactor (PFR), was far less reliable.

The United States began a demonstration fast reactor at Clinch River, Tennessee, near Oak Ridge. When the cost exploded several fold, Congress cancelled the program in 1983. But only in the United States was the parallel reprocessing program also cancelled. Presidents Ford and Carter actually made opposition to reprocessing a government policy, primarily because of fears that widespread reprocessing would increase the risks of nuclear weapon proliferation. President Reagan rescinded the ban, allowing commercial reprocessing. But Congress did not reinstate government financial support, and industry showed no interest in restarting reprocessing.

---

[112] Thomas B. Cochran, Harold A. Feiveson, Walt Patterson, Gennadi Pshakin, M.V. Ramana, Mycle Schneider, Tatsujiro Suzuki, and Frank von Hippel, *Research Report No. 8, International Panel on Fissile Materials, Fast Breeder Reactor Programs, History and Status,* International Panel on Fissile Materials, February 2010, p. 6.

[113] Some Russian engineers and officials may disagree, but the BN type of Russian fast reactor has not been cost competitive with Russian LWRs.

Because of persistent optimism about their fast reactor programs, Britain and France continued with their reprocessing efforts but in the end no fast reactor materialized to exploit the plutonium produced. As a result, the British today have an inventory of 100 tons of separated plutonium,[114]and the French hold 80 tons of separated plutonium.[115]

In spite of British and French experience, the Japanese are now proceeding down the same path, building a reprocessing facility at Rokkasho (as mentioned earlier) and a fast neutron reactor, the Monju. Both have faced severe technical problems, schedule delays, and cost overruns. The Monju reactor was shut down in 1995 after a sodium fire and has not yet restarted normal operation.

Plutonium as Waste

Plutonium is a dangerous component of radioactive waste. When nuclear fuel is fresh from the reactor, its most intense radiation is emitted by fission products, but these tend to fade over timescales of hours to decades; plutonium and other transuranics are more important to the long-term danger over many years to centuries. In addition, one of the challenges of long-term geological disposal of nuclear waste is the heat released by the waste, which can, over decades, raise temperatures to dangerous levels. High temperatures can threaten containment barriers and energize migration of radioactive material. Again, after a few decades, most of the heat comes from plutonium and other transuranics. Finally, plutonium can be used to make weapons, and reactor waste is a potential source of that plutonium.

To deal with the dangers of plutonium, the George W. Bush administration proposed, as part of the Global Nuclear Energy Partnership (GNEP), to separate plutonium and other transuranics and to burn them in fast reactors. These reactors were not breeders. Quite the opposite, they were *burner reactors* designed to consume plutonium without producing more. Plutonium would be separated from LWR fuel, and for every three

[114] International Atomic Enercy Agency, Vienna, *INFCIRC/549/Add.8/11, Communication Received from the United Kingdom of Great Britain and Northern Ireland Concerning Its Policies Regarding the Management of Plutonium Statement on the Management of Plutonium and of High Enriched Uranium*, 2 July 2008.

[115] International Atomic Enercy Agency, Vienna, *INFCIRC/549/Add.5/14, Communication Received from France Concerning its Policies regarding the Management of Plutonium Statements on the Management of Plutonium and of High Enriched Uranium*, 8 September 2010.

or four LWRs, a burner reactor would use the plutonium as fuel to eliminate it by burning it. A single pass through the burner would not consume all the plutonium so the burner reactor fuel itself would have to be recycled several times to completely eliminate the trasnsuranics. Eventually, only fission products would remain—these are an inevitable product of nuclear fission—and these could be sent to a geological repository.

These proposals failed because of the projected high cost of separation and, again, the needed fast reactor was not available. Given the world's inventory of plutonium, several demonstration fast reactors could operate for decades to prove their feasibility before any additional plutonium would need to be separated from existing stocks of used fuel.

The GNEP burner proposal was politically attractive, at least in part, because it seemed to reduce the demand for a geological repository just at the time that the Yucca Mountain geological repository was meeting ever stiffer political resistance. This may also explain the support for reprocessing in France, South Korea, and Japan, where political opposition to permanent disposal is intense. Reprocessing does not eliminate the need for a geological repository and, without a fast reactor, does not even much reduce the need for storage volume, but it does put off for a few decades the political decision about what—and where—a permanent solution should be.

Plutonium for Military Use

In the United States, the production of pure plutonium has been dominated by the requirements of nuclear weapons. The world's first nuclear explosion, on July 16, 1945 near Alamogordo, New Mexico, was powered by plutonium. While nuclear weapons can also use highly-enriched uranium (the Hiroshima bomb was powered by uranium), plutonium is much preferred. It is a complex material and working with it can be difficult, but plutonium allows far more compact and powerful bombs. It is particularly important, for example, in making powerful thermonuclear bombs that are small enough to be able to fit several atop a single missile. Nuclear analysts believe that most large currently-deployed nuclear weapons use plutonium.

In the half century between 1944 and 1994, the United States produced almost 111 tons of separated plutonium metal, almost all of it for the nuclear weapons program, and current inventories are one hundred tons.[116] The nation's arsenal of nuclear weapons

[116] *Plutonium: The First Fifty Years*, op. cit., p. 22.

has declined dramatically since the height of the Cold War, and the United States stopped production of new weapons-grade plutonium 1994.

During the Cold War, old nuclear weapons were continually being dismantled but the plutonium was recovered and incorporated back into new weapons. Now, with the total number of weapons declining, an inventory of unused and unneeded plutonium is building up. Dismantlement continues and thousands more warheads are awaiting dismantlement (the exact numbers are secret), but perhaps more than 14,000 plutonium "pits," the cores of nuclear weapons, are being stored at the Pantex nuclear weapon facility.[117] Several alternatives have been considered for disposal of the excess plutonium, including burying it deep underground.[118] Current plans are to mix 34 tons of the plutonium with uranium fuel in a special facility in Savannah River, South Carolina, and then burn it in commercial nuclear reactors.[119] A ton of plutonium can power a typical commercial reactor for a year. The Russians have agreed to dispose of an equal amount of plutonium from their retired weapons. Even with an inventory of a few thousand active and stand-by nuclear weapons, destroying 34 tons will still leave an inventory of tens of tons of weapons-grade plutonium in storage. Future arms control agreements may include limits on non-deployed, retired nuclear weapons and inventories of plutonium, requiring more plutonium to be destroyed. People who oppose developing a commercial reprocessing and MOX economy may support destruction of weapons plutonium but are concerned that this small-scale MOX project will eventually provide the foundation for a larger commercial operation.

Conclusion

Plutonium is inevitably produced in any reactor that has uranium-238 in the fuel, which today means every commercial reactor. Discussions of plutonium are often complex because people cannot even agree on what it is: an energy source with almost tremendous potential for generating electricity, a dangerous poison that must be locked

---

[117] Robert S. Norris and Hans M. Kristensen, "U.S. Nuclear Forces, 2009," *Bulletin of the Atomic Scientists*, March/April 2009, vol. 65, no. 2, pp. 59–69.

[118] United States Department of Energy, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, January 1997, p. 127.

[119] National Nuclear Security Administration, *Fact Sheet, NNSA's MOX Fuel Fabrication Facility and U.S. Plutonium Disposition Program*, Aug 3, 2010. http://nnsa.energy.gov/mediaroom/factsheets/mox, accessed 15 December 2010.

away, or the explosive power of a nuclear bomb?

Regardless of plutonium's potential in the next century, there are some questions that have to be answered today but many other important questions that can and should be put off until technical developments provide a clearer path ahead. Even with a robust growth in nuclear power, it seems certain that uranium supplies, at affordable prices, will be adequate for several decades, so separating plutonium from commercial reactor fuel to consume it in commercial nuclear power reactors will not be economic. If greater energy extraction were the goal, then "deep-burn" LWRs that start with more highly enriched fuel and burn it longer, which breed and burn plutonium *in situ* are probably a better approach and do not require reprocessing.

To fully exploit the potential of plutonium requires fast neutron reactors. If fast breeder reactors are the long term goal, then research on these reactors should continue but this does not mean plutonium separation is needed now. Any reactors that are built can be fueled for decades by existing inventories of plutonium. If fast reactors ever prove practical and are built in significant numbers, production of plutonium could resume and, given the cushion provided by existing stockpiles, always keep ahead of demand.

Using fast neutron reactors as burners only makes sense if the disposal of transuranics becomes essentially impossible, perhaps for political if not technical reasons. If, a century hence, breeders form the backbone of the nuclear industry, then the last thing we should be doing today is burning plutonium.

Given the technical uncertainties, making an irreversible decision today is ill-advised and it is unnecessary. While there is universal agreement that some form of long-term waste repository will be required, wastes may not need to be committed to a repository right away. Without a long-term repository, the cooling pools at some reactors are filling up, and some utilities have moved waste to above-ground dry casks. These are currently licensed by the Nuclear Regulatory Commission for twenty years at a time, but many analysts believe they should be stable for at least a century or longer. Pending resolution of questions regarding long-term geological storage or fuel for fast reactors, the plutonium can sit in the used fuel rods where it is safe from theft and cannot be used for weapons.

Chapter 8

REQUIRED INFRASTRUCTURE FOR THE FUTURE OF NUCLEAR ENERGY

by Andrew C. Klein

History

The infrastructure needed for revitalized nuclear energy production in the United States can be defined along three general lines: industrial/utility infrastructure including the manufacture/construction of new power plants and the supply chain for both construction and operation; a research and development (R&D) infrastructure including facilities and capabilities in the national laboratories and universities; and the personnel development infrastructure including the university education system and the training programs in industry.

The industrial infrastructure to support the deployment of nuclear power plants in the United States grew up with the fledgling nuclear industry in the 1960s and 1970s as plant concepts were developed, tested and deployed. Power plant vendors and their suppliers developed the necessary supply chain for large- and small-scale components and parts while the utility industry built and operated these large industrial facilities and became comfortable with their operation. In the 1970s this supply chain had become a mature industry and numerous new plants were coming on line in quick succession. However, triggered primarily by the accident at Three Mile Island (TMI) Unit 2 in March 1979 and reduced electricity demand throughout the 1980s, the nuclear power industry went into an extended hiatus of new plant development and construction. This hiatus in nuclear construction turned much of the U.S. industry into suppliers of services instead of suppliers of components and parts. Replacement parts were still available for the nuclear utilities to continue operation, but the domestic supply lines for major components such as steam generators, reactor vessel heads, etc. became a much more international supplier network, dominated by French, Japanese, and South Korean suppliers.

In a similar fashion the nuclear research and development (R&D) infrastructure (both in national laboratories and in industry) grew up from the 1950s through the 1970s to support the development of new reactor concepts, fuel cycles, and reactor designs. Many of these included the construction of testing and demonstration facilities, mostly centered on the application of different reactor cooling technologies and neutron physics. Concerning cooling technologies, the design concepts that were tested and demonstrated included using "light" water (the most common and lightest form of hydrogen bonded with oxygen) or "heavy" water (deuterium, a heavier form of hydrogen, bonded with oxygen). Both forms of water provided needed cooling for the reactor core, but had different abilities to slow down, or moderate, neutrons that governed the occurrence of nuclear reactions inside the core. Other cooling techniques involved helium and other gases. Concerning neutron physics, in addition to thermal reactors that used moderated neutrons, design concepts investigated fast neutron reactors that would use sodium or other liquid metals for removing heat from the core. This was a very heady and exciting time for the development and testing of different nuclear reactor concepts – for applications ranging from power production, radioisotope production, and deployment of nuclear technologies underwater, on the seas, in the air and in space.

Also during this time, the educational and training infrastructure grew up with the nuclear industry as universities added nuclear engineering technology, undergraduate and graduate programs, and utilities developed training programs to supply their workforce needs. Universities developed the facilities and technical capabilities to educate students and perform research that was useful to the national nuclear energy development program. Radiation measurement laboratories, both teaching and research, and research reactors became established on university campuses to help educate scientists, engineers and technicians for the nuclear workforce. Many of these facilities were financed by the federal and state governments to build the personnel development infrastructure for the nuclear industry and to meet their own research and regulatory responsibilities. By the late 1970s more than 60 universities had nuclear engineering educational programs and there were more than 50 university-based research reactors scattered across the United States. Many of the early nuclear engineering educational programs grew from the efforts of Manhattan Project veterans, the early submarine developers at Bettis and Knolls Atomic Power Laboratories, and the early power plant designers at General Electric and Westinghouse. Especially noteworthy was the Oak

Ridge nuclear power school and the establishment by the U.S. government of the Atomic Energy Commission (AEC) fellowship program.

However, after TMI and the reduced demand for electricity that accompanied the oil crises in the 1970s, there was a significant drop in the numbers of students interested in a nuclear engineering or technology education, a commensurate closure of a number of high quality academic programs and the closure of one-half of the operating research reactors during second half of the 1980s and early 1990s. Thus, by 2005 only about 25 academic programs and 27 research reactors remained on university campuses. An especially notable decline was in the number of relevant engineering technology programs whose purpose was expressly to prepare students for skilled trades and technician roles within the nuclear power industry. By the late-1990s only three accredited nuclear engineering technology programs remained in the United States at Excelsior College in New York, University of North Texas in Texas, and Three Rivers Community College in Connecticut.

As the nuclear construction boom ended in the mid-1980s, many nuclear R&D operations in the national laboratories found it difficult to sustain the necessary infrastructure and facilities for nuclear energy development. The U.S. government understood that nuclear energy facilities and reactors were expensive to maintain, let alone refurbish or re-build, and many nuclear experimental facilities were put into maintenance mode.

One important and positive development post-TMI was the establishment of the Institute for Nuclear Power Operations (INPO) in December 1979. INPO's mission is to "promote the highest levels of safety and reliability – to promote excellence – in the operation of commercial nuclear power plants." They accomplish this mission by developing performance objectives, criteria and guidelines for the nuclear power industry and then evaluate every power plant against these objectives. With respect to human capital development, INPO, through its National Academy for Nuclear Training and the independent National Nuclear Accrediting Board, performs training and support for the nuclear industry and the accreditation of the training programs at every nuclear power plant in the United States.

Around 2005 a noticeable change in the level of interest in nuclear power took place. Driven primarily by global warming concerns and the need for increases in electricity generation without the production of greenhouse gases, nuclear energy was again considered to be a potential electricity supplying technology by both the utility community and the U.S. government. The government began to publicly acknowledge the need for a role for nuclear power in the energy mix of the United States, and utility executives began planning to build new nuclear power plants. Some of this was fueled by funding levels for federal loan guarantees for the construction of new nuclear power plants and for research and development that started to become available from the U.S. Department of Energy (DOE) in the late 2000s. This increased level of interest in new nuclear power has continued to the present.

At the same time, many more students entered the remaining university nuclear engineering programs, in some cases more than quadrupling the enrollments seen just a few years earlier. Utilities began working together to resurrect technician training and skilled trades development programs, mostly local to their operating power plants, but also collectively in anticipation of the construction of new nuclear power plants. These new programs are aimed at producing graduates able to work as technicians, especially in electrical, mechanical, chemical, welding, and in some cases nuclear vocations. These specialists will be needed to operate the current fleet of nuclear power plants as well as be capable of building and operating a new generation of nuclear power plants. New academic programs began to be discussed by universities and DOE, and the Nuclear Regulatory Commission (NRC) began new university research, development, infrastructure and student support programs that attracted new universities and students into nuclear energy related academic programs.

Current Status

Currently, there are 104 operating reactors in the United States and an existing, robust supply chain available to continue the operations of these plants through their licensed lifetimes. Most of these reactors have either received or will receive a 20-year license extension to extend their operational lifetime to at least 60 years. Additional license extensions are also possible beyond 60 years. Research and development activities are currently being conducted to determine the information and regulatory needs to enable these additional license extensions.

New reactor license applications have been submitted to the NRC with a few additional units and sites still under consideration. As of 2010, the industry has expressed interest in as many as 26 new reactor units at 17 different sites. However, it is uncertain how many of these reactors will actually be completed over the next 20 years, but many of these are quite possible. The highest probability would be for those who receive loan guarantee assistance from DOE. Financing these large projects is the greatest impediment to their completion. Successful completion, start-up, and operation may give other sites and plants the opportunity to consider completion without loan guarantees, but this is yet to be determined. Additionally, at least three new sites have been chosen and significant progress has been achieved in the development of new uranium enrichment facilities across the United States. Some of these projects have already received loan guarantees, which would increase the likelihood of their successful construction and operation.

These new plants will require a robust supply chain of nuclear manufacturers. Nuclear power plants are complex undertakings that require hundreds of components and subcomponents and the construction of numerous new power plants will, according to the Nuclear Energy Institute (NEI), "require a deep and diverse supplier base." With the idea of supporting the maintenance of existing nuclear suppliers and the development of new suppliers NEI has developed a "Supply Chain Map of Nuclear Reactor Components."[120] This map is broken down into four main categories: nuclear island, turbine island, balance of plant, and site development and construction and is aimed at assisting new suppliers to identify where their products fit into the components and subcomponents of new nuclear reactor designs and to enable them to better understand the quality requirements for these components.

The quality standards for many nuclear power plant components, particularly those critical to reactor safety, have been well-established. These standards and requirements ensure that a nuclear facility's structures, systems, components and controls can be relied on to be functional and operational under the most rigorous safety conditions. Those components that are subject to these rigorous standards are often known as "nuclear-grade" or "safety-related" components. Any manufacturer of these components must have appropriate quality assurance (QA) programs in place in order to ensure that the standards are met.

With respect to the QA programs for new reactors, NRC will review and inspect these programs and their implementation for nuclear steam system suppliers, architect-engineering firms, suppliers of safety-related and commercial-grade products and services, all calibration and testing laboratories, and all holders of NRC construction permits, operating licenses, and combined licenses. By conducting inspections, the

[120] Nuclear Energy Institute, "Supply Chain Map of Nuclear Reactor Components," http://www.nei.org/filefolder/Supply_Chain_Map_v2.pdf

NRC's main objective is to determine whether licensees and their contractors are meeting the agency's requirements through the implementation of procedures, recordkeeping, inspections, corrective actions, and audits.

An important development in the management of the nuclear R&D infrastructure within the DOE was the designation in 2004 of DOE's Office of Nuclear Energy as the Lead Program Secretarial Office (LPSO) for the Idaho National Laboratory (INL) and the identification of the consolidated INL as the lead national laboratory for nuclear energy science and technology development. This has allowed the Office of Nuclear Energy to focus on maintaining and developing the needed R&D capabilities and facilities at INL. Some support also remains for the other national laboratories that have significant capabilities in certain aspects of nuclear energy development, most notably at Oak Ridge (ORNL), Argonne (ANL), Sandia (SNL), and Los Alamos (LANL) national laboratories.

Currently, the nuclear industry uses a wide spectrum of high school, community and technical college as well as university graduates from the B.S. to Ph.D. The nuclear industry, consisting of the vendors and manufacturers, the architects, designers and engineers, the construction companies, and the utilities and power plant operators, use a broad spectrum of educated and trained personnel. Government agencies such as DOE (and its national laboratories), NRC, the Department of Defense, the National Nuclear Security Administration, the Defense Intelligence Agency, the Defense Threat Reduction Agency, the Federal Bureau of Investigations, the Food and Drug Administration, the U.S. Department of Agriculture, the U.S. Department of State, and the Environmental Protection Agency all employ people who have education and training in nuclear specific areas. Finally, academia also requires people to fill roles as faculty, staff, and researchers.

The nuclear industry requires many people with a broad spectrum of education and training backgrounds. The range of skilled people needed include engineers (not only nuclear, but mechanical, structural, chemical, electrical, civil and construction engineers), health physicists, plant managers, lawyers, managers and accountants, skilled trades-people in mechanical, electrical, maintenance, and construction, nuclear safeguards and security experts, architects, risk assessment specialists, and others. NEI has conducted workforce surveys over the past decade and identified the most difficult employee characteristics to recruit into the nuclear utility industry. There is little reason to expect that this will be any different for new plants. The people that NEI has identified as being hardest to find, in order of difficulty, are female candidates, minority candidates, nuclear engineers, experienced designers, non-destructive evaluation technicians and health physicists. Specific emphasis has been placed on developing targeted recruiting in many of these areas through awarding scholarships and fellowships, internships and other methods of supporting students. Also DOE has developed educational modules aimed at middle and high school students to enhance their awareness of these high paying career opportunities.

The Future

Looking to the future, or more specifically the next 10 to 20 years, there will be a continual need to revitalize the supply chain for the nuclear industry. Since the market for new nuclear power plants is fully established as a global one, the supply chain will continue to develop with an international character. U.S. utilities and consumers of electricity will benefit from a competitive market for the supply of nuclear reactor systems, parts, and components. U.S. suppliers of these systems, parts, and components must be enabled to effectively compete if they are to remain strong participants in this marketplace. Also, as the new reactor concepts become better developed and understood, the supply chain will need to be developed to ensure that suppliers with appropriate quality programs are prepared to deliver the needed equipment, people, and services. Continuing and potential future bottlenecks in the supply chain will probably include large forging capabilities for pressure vessels, steam generators, and other large components as well as for some of the specialty materials needed by the nuclear industry. In some cases, such as large forging capabilities, the United States will continue to rely on foreign manufacturers of these important components of nuclear power plants.

The emergence of the technologies for new small- and medium-sized, modular reactors that respond to the high initial capital cost of building new power reactors is a welcomed recent development. These highly creative design concepts, some of which are new ideas while others are older concepts that have been reinvigorated by the prospects of new market possibilities that may come along through small reactors, are aiming to develop a new financial paradigm for the nuclear industry by enabling utilities, or even non-electricity generating owners, to incrementally add small unit sizes, typically ranging from 10 to 300 megawatts of electricity. The idea is that smaller unit sizes can be added one at a time, more quickly, and in a modular fashion, rather than requiring the construction of individual large-scale power plants. The developers of these new, smaller concepts are proceeding toward design certification with the NRC and developing the financial and business cases that may allow their installation by customers, both domestic and overseas, who would not have considered nuclear power in large increments because their financial situations or electric grid capabilities would not enable them to accommodate the introduction of large single-unit power plant additions.

One potential limiting capability will be the development of the people who are educated and trained to operate these new small reactor systems. The leading concepts being considered are evolutionary developments from current light water based nuclear reactors and the skills needed to operate these systems may not be far from those needed to operate current technologies. However, testing facilities will be needed for these new concepts, in both integral and separate-effects forms, to provide validation and verification of the computer codes used to predict their performance during both normal and accident conditions.

A few special technologies and materials are important to the new nuclear energy industry and may need special attention to ensure their availability when they are needed. Specialty materials, such as zirconium, hafnium, gadolinium, beryllium, and others, will need suppliers to provide processing, manufacturing, and recycling technologies that are cost-effective to the manufacturers and utilities building new nuclear power plants. Some, but not all, of these specialty materials have other uses in the economy but their availability to the nuclear industry needs to be ensured.

Today's nuclear R&D infrastructure in the nation's national laboratories is rather aged. Many of the nuclear R&D facilities across the complex of national laboratories were originally developed in the 1960s and 1970s. However, while they may be old, many critical facilities have seen reasonable maintenance and upgrades over the years so that a basic capability remains available. DOE continues to review its infrastructure needs on a regular basis, including updates to the ten-year site plans at each national laboratory and facility reviews conducted by the National Academies of Science and Engineering, the DOE Nuclear Energy Advisory Committee and others. These reports periodically give the government and the public insight into the capabilities and needs of the nuclear energy R&D community and are used by DOE to guide their annual budget requests to Congress. All of the facilities that researchers might want may not readily be available, but a basic infrastructure has been maintained for R&D activities and a process for their maintenance and expansion is available annually to DOE.

A few skilled technical areas related to construction of new nuclear power plants have not been used over the past 20 years in the United States. Since very few new plants have come on-line, there has been little need for people trained in nuclear plant construction and plant startup/test engineering. These highly specialized skills previously were available while new plant projects were being brought on-line during the 1970s and 1980s; however, new education and training programs will be needed to make sure that people are ready when the new plants begin to load fuel and contemplate full operation. Also, should the recycling and reuse of nuclear fuel reach a mature stage of development over the next 30 years, there will be a significant need for radiochemists and radiochemistry technicians, and the development of education and training programs for recycling facility engineers, technicians and operators.

Competing interests for a top quality workforce will come from various sectors, both inside and outside of the nuclear industry. The electric utility industry, including all means of production and distribution of electricity will look for similarly educated and trained personnel. The defense, telecommunications, oil and natural gas industries will also be searching for highly educated and trained workers. However, utility careers are sometimes viewed by students to be low-technology career paths of lesser excitement when compared to other high-technology options, and thus the electric utilities must offer competitive compensation packages in order to recruit the best personnel into the nuclear industry.

One important aspect of the nuclear energy pipeline for both personnel and equipment is the long design lifetimes for nuclear power plants relative to the length of time that is typical for any one individual. Current nuclear power plants have initial design and license lifetimes of 40 years. Most, if not nearly all, currently operating nuclear power plants in the United States will receive a 20-year license extension from the NRC. Some of these plants may be able to gain an additional 20-year license extension, if current research and development activities show that they can clearly be operated in a safe manner. The new power plant designs all have initial design lifetimes of 60 years, and conceivably their licensed lifetimes could extend to 80 or 100 years. If five to 10 years are required to construct a plant and then another five to 10 years to decommission it, the plant's total product lifetime approaches 110 to 120 years from conception to dismantlement. This is considerably longer than the product lifetime for any other industrial product. Compare this to the roughly 40-year productive career that is typical for most workers. This difference emphasizes the need for continuous education and training of the nuclear workforce.

Universities that teach nuclear engineering are all "research intensive," and faculty are often focused upon getting research grants and contracts and then performing the research. They use graduate students and postdoctoral researchers to accomplish this research, which typically is on the cutting edge of the nuclear energy industry. The financial structure of the modern research university puts great emphasis on research funding to support the activities of the faculty and students which often forces them to focus on finishing the current research while constantly looking for the next grant or contract. Over the years, this combination of driving forces within the modern research university with a narrow focus available for research support from government and industry sponsors may yield a nuclear science and engineering faculty that is insufficiently diverse to teach the broad topical areas that are needed by the nuclear industry. Students coming through the U.S. academic programs are often exposed to advanced concepts, without obtaining a clear understanding of the current nuclear power fleet and the types of reactors that are likely to be operational during their careers. Schools that have access to commercial plant simulators and that are able to incorporate them into their academic programs can provide a significant stimulus for students to become directly interested in working in the current nuclear power fleet.

Finally, there is a significant continuing need for educational and training infrastructure in order to maintain the appropriate technically relevant nuclear workforce. This infrastructure in the college and university systems includes state-of-the-art classrooms and teaching laboratories, instrumentation and radiation measurement capabilities, heat transfer, fluid flow and radiochemistry laboratories, system operation and simulators, and computational capabilities. An increasingly important aspect of today's education and training infrastructure is the ability to deliver and receive distance education and classes that are available for students to take at any time of the day or night. While on-site resident education will remain an important aspect of the university development of scientists and engineers, these new delivery mechanisms are rapidly and continuously increasing in quality and capability. In the training realm plant simulators and hands on training for maintenance and installation of plant components such as valves, pumps, piping, fuel handling tools, etc. are needed. One particular type of simulator that is very useful is a radiation area simulator which enables workers to become accustomed to and familiar with working around radiation, point and surface radioactivity, and urface contamination, etc. The aim here is to best prepare workers for working with and around radioactive materials and remove their fear of the unknown.

Chapter 9

ALTERNATIVES TO NUCLEAR POWER

by Richard Wolfson

What sources might substitute for nuclear energy? That depends on who's asking. If you're a utility executive, nuclear energy's chief virtues are low cost and its supply of baseload power. Nuclear plants, that is, run at full power nearly all the time, supplying loads that are always present. And nuclear plants are large, capable of powering entire cities. So a utility looking to replace a nuclear plant with "plug and play" economic and grid compatibility is likely to seek large, low-cost, steady, reliable sources—criteria best met by coal- and gas-fired plants.

If you're a consumer or business watching your bottom line, you'll want cheap replacement power. That, too, is likely to come from fossil-fueled power plants, unless you're in a region with ample hydroelectric resources. Natural gas affords the lowest capital costs, but gas prices fluctuate. Coal prices are steadier, but capital costs of coal plants are greater. Economic and regulatory conditions might greatly alter this comparison; tightened environmental constraints, a carbon tax, or a requirement for carbon capture and sequestration could make coal less attractive economically.

An environmentalist will value sustainability and minimal environmental impact—especially low carbon emissions. Wind and solar, accounting for a small but rapidly growing share of the U.S. electrical energy mix, would be leading choices. But these renewable energy sources, unless linked through "smart grid" technologies covering vast geographical areas, are too intermittent to qualify as baseload power. So an environmentalist interested in replacing nuclear plants with solar and wind will also advocate a substantial upgrading and "smartening" of the electrical grid.

A state utility commissioner, concerned for stability in pricing and availability of future energy supply, might want to keep the low-cost energy from established nuclear plants in the mix. But if nuclear energy must be replaced, a prime utility-commission choice might be long-term contracts with big hydroelectric producers—if they're available for import from nearby states or, as with the vast hydro resources in

Canada, across national borders.

Nuclear energy itself could be a substitute for today's generation of light-water fission reactors. Advanced nuclear alternatives include breeder reactors that would greatly expand the nuclear fuel resource; fast-neutron reactors that could "burn" nuclear waste; fission-fusion hybrids; and, ultimately, pure fusion reactors that could, if economical, provide nearly limitless energy for billions of years. But, with the exception of a worldwide handful of breeders with spotty operating records, none of these nuclear alternatives is ready for commercial use.

The answer to the "nuclear substitute" question also depends on scale and timing. If you're talking about replacing a single nuclear plant, then you have available the whole range of conventional energy sources, or you can move in new directions. There's power to spare in today's electric generating industry, so your choices today aren't necessarily constrained by availability. But if you're the entire United States, with 20 percent of its electrical energy from nuclear plants, then a decision on substitute power may face serious constraints. Timing matters, too: If you're talking about replacing the entire nuclear power enterprise over several decades, then there's time to develop new sources, conventional or otherwise. But if you're looking at nuclear plants that will go offline in the next few years, then you'll have to scramble to line up replacement sources—whether than means contracting with existing suppliers or developing new generating capacity.

Finally, you might prefer an energy strategy that does away altogether with the need to substitute for nuclear power, by reducing demand to the point where the nuclear contribution is no longer needed. That's an admirable goal, but with nuclear plants providing 20 percent of the United States' electricity, it's not one that could be implemented overnight.

Getting Quantitative

Whatever your choice or choices for nuclear substitutes, they've got to meet one rigid criterion: They must be capable of supplying energy—reliably and almost continuously—at the same rate that the nuclear industry does now. *Power* is the rate of energy supply or consumption, so that means the power output of your substitute sources must at least equal that of the nuclear plants you're replacing.

In 2010 there were 104 commercial reactors operating in the United States, down from a peak of 112 in 1990. These reactors produced just over 20 percent of U.S. electrical energy—a yearly total of some 800 terawatt-hours (TWh; see Box 1). The

104 reactors had a combined electric generating capacity of 101 gigawatts (GW_e)—meaning that if they ran continuously, the electrical energy they produced, in gigawatt-hours, would be that power multiplied by the number of hours in a year: 885,000 GWh or 885 TWh. Comparing with their actual 800-TWh annual energy production shows that the reactors' average *capacity factor* was nearly 91 percent—meaning that, on average, each reactor produced its rated power 91 percent of the time. Bottom line: Substituting alternative sources for the entire U.S. nuclear energy enterprise would require providing electrical energy at the rate of 800 TWh per year. Nearly all suitable nuclear-replacement energy sources are already represented in the United States' electrical energy mix, shown in Fig. 1, although in the long term additional sources could become available.

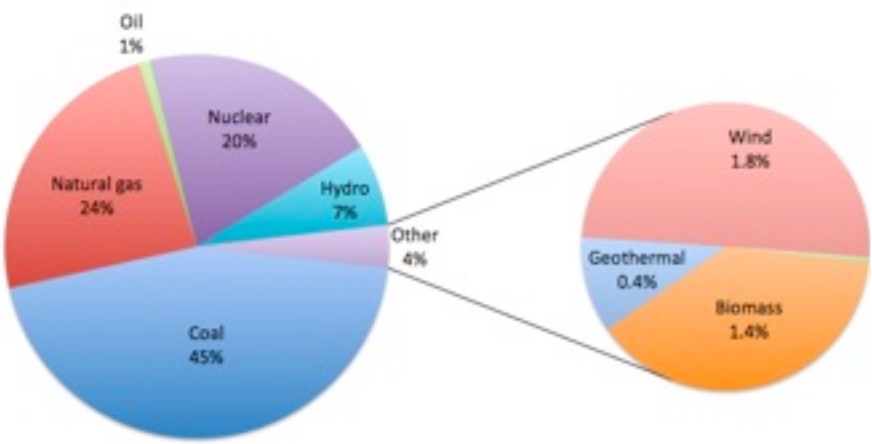


Figure 1   Sources of electrical energy in the U.S. (Source: U.S. Department of Energy, *Annual Energy Review 2009*, Table 8.2a, 2009 data).

Power—the rate of using or generating energy—is measured in *watts* (W). Electric power plants have typical outputs ranging from a few megawatts (millions of watts; MW) to several thousand megawatts; 1000 MW is 1 gigawatt (one billion watts; GW). The United States' total energy consumption rate is about 3.5 terawatts (TW, or trillion watts, with 1 TW = 1000 GW). That's just under one-fourth of the world energy consumption rate of 16 TW, and it amounts to about 10 kW per capita.

Is that 10 kW per day, or per year, or what? Neither; it's a *rate*; "per time" is built in. The average U.S. resident uses energy (all forms, not just electricity) at the rate of 10 kW, round the clock, day in and day out.

Since power is energy per time, energy can be measured in watts multiplied by time. One such unit is the kilowatt-hour (kWh), familiar from your electric bill. One kWh is the energy consumed by a 1000-W stove burner, left on for one hour. It's also the energy consumed by the average U.S. resident in 6 minutes (10 kW for one-tenth of an hour). For larger amounts of energy, we use similar combinations of power multiplied by time; for the U.S. nuclear industry, for example, yearly energy outputs are conveniently measured in terawatt-hours (TWh, equivalent to 10^{12} watt-hours or a billion kWh).

The average efficiency of electrical energy generation in the United States is between 30 and 40 percent, due to inefficiencies in the fossil-fueled and nuclear plants that produce nearly all our electricity. That means power plants typically convert to electricity only 30-40 percent of the energy in their fuels. Thus, for every kilowatt-hour of electrical energy a nuclear plant produces, it discharges about two kWh of energy as waste heat. This inefficiency leads to the distinction between electrical output and thermal power extracted from fuel. A power plant rated at 1-GW_e, for "1 gigawatt *electric*," would extract fuel energy at the rate of about 3 GW_{th} ("3 gigawatts *thermal*"). But only one of those gigawatts gets converted to electricity.

The Fossil Alternative

In 2009, fossil fuels accounted for 70 percent of electric power generation in the United States—coal for 45 percent, natural gas for 24 percent, and oil—more valuable as a transportation fuel—for just under 1 percent (see Fig. 1). Domestic coal is abundant and will be for decades to centuries. Gas supplies are more limited, but should be ample for several decades. In contrast to oil, where imports account for two-thirds of the U.S. supply, only about 12 percent of U.S. gas consumption is imported. So, from a resource standpoint, fossil fuels could provide a viable substitute for nuclear power.

Although some are smaller, most commercial nuclear reactors have power outputs in the 1-GW_e range, and often two or more reactors at a site make a power complex with output of several GW_e. The largest coal-burning plants in the United States have comparable outputs, often with pairs of generating units each in the 1-GW_e range. In contrast, natural gas plants have typical outputs measured in hundreds of MW_e. So it would take several natural gas generating stations to replace a nuclear plant. But natural gas plants are relatively easy and quick to construct—making natural gas probably the easiest source to substitute directly for nuclear power.

Fossil fueled power is environmentally problematic. Despite substantial improvements resulting from the Clean Air Act and its amendments, coal plants continue to pollute the atmosphere, land, and water with toxic substances ranging from sulfur to mercury to particulates. Combustion of gas is cleaner, making gas preferable from a pollution standpoint. But the big environmental issue with any fossil fuel is its climate-changing carbon emissions. On this score, gas is also preferable: it produces about half the carbon dioxide of coal for the same electrical energy production. And gas plants using combined-cycle technology—incorporating jet-engine-like gas turbines whose waste heat powers a conventional steam turbine—can achieve efficiencies of 60 percent, well above the best coal or nuclear plants. No energy source is completely free from emissions of carbon dioxide or equivalent climate-changing greenhouse gases, and nuclear is no exception. Worst-case estimates for nuclear power involve greenhouse emissions per unit of electrical energy that are 20 percent of those from the best natural gas plants—and the nuclear emissions could be a lot lower. Substituting natural gas for nuclear power would, therefore, result in substantially increased greenhouse emissions. But its availability, economics, ease of implementation, and environmental advantages over coal make natural gas the obvious choice as a fossil substitute for nuclear power.

Renewable Energy

Renewable sources of electrical energy include hydro, geothermal, biomass, wind, and solar—although depending on how they're harvested or extracted, biomass and geothermal may or may not be sustainably renewable. Whether and how well these renewables might substitute for nuclear power depends on the total power capability of each renewable source, on temporal and geographical availability, on economic factors, and on the state of each technology and its manufacturing base.

Hydroelectric power

Figure 1 shows that 7 percent of U.S. electricity currently comes from hydropower, which captures the energy of flowing or falling water. Hydropower was one of the earliest sources of mechanical energy for industry, and became prominent in the generation of electricity in the early 20th century. But in the United States, hydropower is unlikely to substitute for nuclear because our hydroelectric potential is almost entirely exploited. Imported hydropower is a different story, as ongoing hydro development in northern Quebec makes power available for sale to the northeastern United States. The state of Vermont, which gets one-third of its electrical energy from a nuclear plant that may soon be shut down, is considering replacing its nuclear electricity with purchases of Canadian hydroelectricity. But replacing all 20 percent of U.S. nuclear-generated electricity with hydropower is probably unrealistic.

Geothermal power

Where vapor-saturated hot rocks lie close to Earth's surface, geothermal steam can be used directly to drive a turbine-generator to make electricity. More complex power plants can extract energy from lower-quality geothermal resources, at greater expense but with less environmental impact. In principle, holes several miles deep bored into hot, dry rock anywhere on Earth could yield geothermal steam from water pumped down the holes, but that technology is hardly developed. A deep-hot-rock project in Switzerland was halted in 2006 after it triggered an earthquake. Today about 0.4 percent of U.S. electrical energy is from geothermal sources, a figure that is not likely to rise substantially. Therefore geothermal energy is unlikely to make a significant dent in the 20 percent of U.S. electricity generated from nuclear fission.

Biomass

About a third of the "other" category in Fig. 1 represents electricity generated from burning biomass—ultimately stored solar energy captured by photosynthetic plants. About two-thirds of biomass electricity comes from wood, usually as chips, burned to power conventional steam-cycle turbine-generators. The remainder is from combustion of municipal waste, landfill gases, and other fuels that are ultimately biological in origin. Although liquid biofuels may play increasing roles in transportation, supply limitations and logistical constraints probably rule out much use of biomass for large-scale electric power generation. The largest wood-fired power plants have outputs in the range of 50 MW_e, far below the GW_e-range outputs of nuclear plants. Local situations excepted, biomass is unlikely to provide a wholesale substitution for nuclear power.

Wind

Some 1 percent of solar energy incident on Earth goes into driving winds—energy that we can tap directly with wind turbines. A 2010 report by the National Renewable Energy Laboratory estimates that the United States' land-based wind resource could support wind installations totaling some 10 TW of peak power. Even accounting for wind's relativity low capacity factor—about 36 percent for new U.S wind installations—that still translates into a potential for about 33,000 TWh of annual electrical energy production. Comparison with nuclear power's annual production of 800 TWh shows clearly that wind has the potential to substitute for nuclear power.

That substitution, however, would not be "plug and play." Nuclear plants can be sited most anywhere there's cooling water available—usually close, but not too close, to the population centers they serve. But the United States' greatest wind resources are in the Great Plains, a region of low population density. Supplying the U.S. population with wind-generated electricity would, therefore, require substantial upgrades to the long-distance transmission capabilities of the North American electrical grid. And the intermittent nature of wind makes it difficult to manage electrical distribution when wind-generated energy is added to the mix.This intermittency is not a significant problem when wind's percentage of the mix is small, but as it rises above about 20 percent, problems of managing wind energy become more serious. One solution is to link geographically distant wind sites on the assumption that there will always be wind energy available somewhere. That, too, requires substantial upgrades to the electrical grid.

Today's wind farms have peak power outputs in the hundreds of megawatts; coupled with the 36 percent capacity factor, that makes them considerably smaller than typical nuclear plants. So something like ten 300-MW wind farms would be required to replace a 1-GW nuclear plant—and they would occupy some ten times the land area of the nuclear plant and the mines and processing facilities that supply its fuel. But unlike land dedicated to nuclear energy, land occupied by wind farms remains suitable for ranching and other low-density agricultural uses.

Overall, the issues associated with wind-generated electricity are not trivial, but neither are they insurmountable. Furthermore, wind capacity is growing at more than 30 percent annually, and wind is approaching cost-competitiveness with fossil fuels and is arguably less expensive than new nuclear installations. A decade ago, wind's contribution to the U.S. electricity mix was negligible; today, wind produces some 2 percent of U.S. electricity. Wind clearly offers a realistic if not fully grid compatible substitute for nuclear power.

Solar

Conversion of solar energy into electricity occurs either with solar-thermal systems or through photovoltaic (PV) panels. Like their fossil and nuclear counterparts, solar-thermal systems use heat energy to drive turbine-generators. Semiconductor-based PV panels convert sunlight energy directly into electricity, with no moving parts; typical efficiencies of commercial panels are 10 – 20 percent. The largest solar-thermal installations currently operating in the United States are rated at just under 100 MW_e, while the largest U.S. PV installation is 14 MWe. Worldwide, photovoltaic capacity is growing at nearly 40 percent per year, and PV "farms" are approaching 100 MW in peak output. There's no question that the solar resource is adequate: solar energy reaches Earth's surface at the rate of about 100,000 TW, nearly 10,000 times the rate at which humankind uses energy.

Many of the same considerations apply to solar as to wind. There are issues of intermittency and remoteness of optimal solar locations. Solar, unlike wind, is not currently economically competitive with conventional power generation—although costs are dropping rapidly. Figure 1 reflects this economic disparity, with solar producing a mere 0.02 percent of U.S. electrical energy. On the other hand, solar lends itself better than wind to so-called distributed generation—for example, individual rooftop systems—offering an alternative to a power system based dependent on relatively few gigawatt-scale power plants. Some solar-thermal plants reduce intermittency through thermal-energy storage, which can increase capacity factors from 25 percent to around 70 percent. And solar-thermal installations, because they use conventional steam turbines to drive electric generators, can be coupled with non-solar heat sources, usually natural gas. Such hybrid solar-gas plants offer steady power outputs with reduced fossil fuel consumption.

Nuclear Alternatives

If the goal in replacing today's nuclear power plants is to get beyond light-water reactors first developed in the 1950s, then advanced nuclear technologies should be considered as substitutes. Most of the 100+ reactors operating today in the U.S. are nearing the ends of their original design lifetimes, and while most are receiving 20-year license extensions from the NRC, they will need replacing if nuclear power is to hold its own in the U.S. electricity mix. Advanced fission reactors offer advantages in safety, in prolonging the uranium supply, and even in "burning" the waste from current-generation reactors. Development of fusion reactors would make every gallon of seawater the energy equivalent of 300 gallons of gasoline—providing humankind with energy for billions of years longer than the sun will continue to shine. But none of these advanced nuclear alternatives is anywhere near technological or economic feasibility, and it will be decades before any become viable substitutes for today's light-water fission reactors.

Conclusions

So what's the best substitute for nuclear power? Again, that depends on your criteria and timeframe. Fossil-fueled power from coal or gas offers proven technology, relatively low cost, and fuel availability for decades or longer. Gas plants are quick to construct and could readily replace aging nuclear plants. But in a world experiencing rapid climate change, fossil-generated energy is a step backward from necessary reductions in greenhouse-gas emissions. The one large-scale, mature-technology renewable replacement for nuclear power is hydroelectricity—but in the United States there's little potential for growth in hydro. Geothermal energy is limited to a few geographical regions and cannot make major inroads into that 800-TWh per year of nuclear electricity. Biomass, while potentially significant for transportation, is unlikely to see greatly increased use for generation of electricity. Renewable energy from wind and the Sun is abundant and has minimal—but not zero—environmental impact. Wind is becoming competitive with conventional energy sources, and growth in the wind industry has brought wind to a 2-percent share of U.S. electricity generation, a figure that is rising rapidly. Solar-thermal and photovoltaic technologies are farther behind economically, but their advantages are similar to those of wind. Both wind and solar challenge the power grid with their intermittent generation, and increased use of these renewable energy technologies would require an enhanced and smarter electric grid. Finally, advanced nuclear technologies could replace today's fission reactors while essentially solving the nuclear waste problem. But they're decades away.

Comparing nuclear power and its potential replacements depends not only on technological and immediate economic issues, but also on policy decisions that could alter the future balance on these issues. Tax incentives for wind and solar encourage nascent industries, lowering costs and encouraging widespread dissemination. Funding to develop carbon capture and sequestration could make coal more attractive from an environmental standpoint. Advanced reactor designs, and especially fusion, require research collaborations and funding at the international level. Finally, accounting for negative externalities—especially greenhouse emissions—in the cost of fossil energy would make renewable alternatives to nuclear power more competitive.

If the United States' nuclear enterprise is to be replaced, that will most likely be done with a combination of sources, beginning with fossil fuels and, over time, substituting renewable sources. In the end, there's no one right choice to replace nuclear power. Geography, economics, resource availability, and related factors may dictate a mix of nuclear substitutes that vary throughout the country. But before plunging into nuclear replacement, there's another question to be asked, one that won't be answered here: Why replace nuclear power? There are plenty of good reasons, mostly involving negative aspects of nuclear power, but they need to be weighed against the negatives associated with substitute energy sources and with the fact of an established industry that economically generates 20 percent of the United States' electricity—and that does so more safely and with less environmental impact than its most obvious replacement, namely fossil-fueled energy.

Chapter 10

EMERGING NUCLEAR TECHNOLOGIES

by Daniel Ingersoll

Commercial nuclear power presently addresses only one of the United States' energy needs: centralized base-load electricity generation. It is possible to extend the use of nuclear energy to other energy demands, such as distributed electricity generation and industrial process heat applications; however, these applications may be better served by a different plant design and underlying technology than the existing fleet of water-cooled reactors. Even for electricity production, advanced technologies and innovative reactor designs can significantly improve the affordability and utility of nuclear energy for meeting U.S. energy needs. This realization has given rise to a vigorous advanced reactor development effort in the United States and internationally.

Background

The terminology of reactor "generations" was introduced in the late 1990s in part to clarify the roles and opportunities for developing advanced nuclear technologies. Generation I designs represent the early prototypes that were designed and built to gain familiarity with the technology, and provided the basis for the existing fleet of commercial light-water reactor (LWR) plants, which are categorized as Generation II. During the U.S. hiatus of new plant construction in the past three decades, several Generation III plant designs were developed that incorporated lessons learned from the previous generation of plants, especially regarding design simplification, standardization, and increased use of passive safety features. But since U.S. utilities continued to purchase other energy sources, principally naturally gas, to meet new capacity requirements, no Generation III plants were ordered and constructed. With a resurgence in the interest in building new nuclear capacity during the past several years, updated versions of some of the Generation III designs, referred to as Generation III+ designs, were developed and are now in the process of being fully licensed and ready for construction. An example of a Generation III+ design is the Westinghouse Advanced Passive (AP-1000) design. The first four AP-1000 plants are under construction in China and another four units have been ordered in the United States.

Generation IV Technology

About the same time as the development of the Generation III+ designs for immediate deployment, several Generation IV concepts were initiated by the research and development (R&D) community. The Generation IV concepts represent a broad set of advanced reactor concepts that are intended to dramatically improve the performance of previous generations, especially with regard to safety, economics, sustainability, and proliferation resistance. Moreover, they are intended to enable the extension of nuclear energy to more than base-load electricity production. The Generation IV program was initiated in the United States in 2000 and was quickly embraced by a consortium of countries—initially seven and now thirteen countries, including: Argentina, Brazil, Canada, China, Euratom, France, Japan, Russia, the Republic of Korea, South Africa, Switzerland, the United Kingdom, and the United States.[121] Each country funds its own participation and actively collaborates with the United States in the development of advanced reactor concepts and associated technologies.

The Generation IV program began with an extensive review, evaluation and selection of six specific reactor concepts:

- Very High-Temperature Reactor (VHTR),
- Super-Critical Water-cooled Reactor (SCWR),
- Molten Salt Reactor (MSR),
- Sodium-cooled Fast Reactor (SFR),
- Lead-cooled Fast Reactor (LFR), and
- Gas-cooled Fast Reactor (GFR).

These six reactor concepts, which actually represent classes of reactor systems rather than specific designs, can be further grouped into two fundamental categories: (1) high-temperature reactors principally for process heat applications, and (2) fast-spectrum reactors principally for fuel cycle applications. While all six reactor concepts can be used to produce electricity, some with significantly higher conversion

121 "A Technology Roadmap for Generation IV Nuclear Systems," GIF-002-00, December 2002.

efficiencies than traditional light-water reactors, their real strength is in addressing non-electrical energy demands. While the United States initially studied the viability of all six Generation IV concepts, it became evident that two systems, the VHTR and the SFR, were the most mature in their class and were selected for more in-depth development.

High-Temperature Reactors

The VHTR is largely intended to extend nuclear energy into non-electrical applications. Electricity generation represents roughly 40 percent of U.S. total energy consumption, and similarly about 40 percent of U.S. greenhouse gas (GHG) emissions.[122] To significantly reduce our total GHG emissions will require at least a partial replacement of fossil fuels used for industrial process heat and for transportation fuels. Reducing fossil fuels for transportation can be accommodated through increased use of plug-in electric vehicles, but may also require a move to cleaner liquid fuels such as hydrogen. The de-carbonization of industrial energy consumption will require adaptation of nuclear energy to process heat applications, many of which require process temperatures well above what can be delivered from conventional LWRs, which are limited by the low boiling temperature of water. While conventional water reactors can provide output temperatures of 300-350°C, many industrial processes require temperatures >500°C and even as high as 1000°C. As shown in Fig. 1, examples of high-temperature processes include steam reforming of natural gas, coal gasification, and thermo-chemical production of hydrogen. To achieve the very high temperatures, reactor designers must shift to another coolant technology such as gas, super-critical water, or molten salt, and must also switch to different materials of construction that can survive sustained operation at elevated temperatures.

---

[122] "Inventory of U.S. Greenhouse Gases Emissions and Sinks: 1990-2007," EPA-430-R-09-004, April 15, 2009.

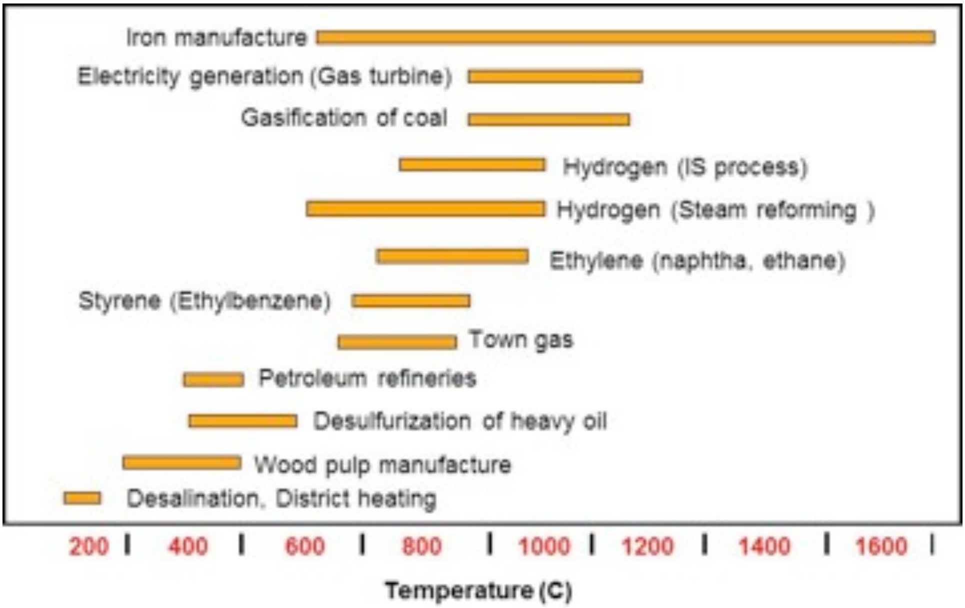


Fig. 1. Temperature requirements for various industrial processes[123]

Helium is a natural choice as a coolant for high-temperature reactors because it is inert, remains in single phase throughout the postulated temperature range of operation, and has accumulated considerable international experience for nuclear systems. The United States built two helium-cooled prototype reactors: Peach Bottom 1 and Fort St. Vrain. Typically, graphite provides the neutron moderation function in helium-cooled reactors and also provides good thermal inertia, which is important for slowing down the response of the reactor to power transients. Multiple VHTR designs are being developed, including designs that use fuel in stationary "compacts" that are replaced on a regular refueling cycle, and designs that use fuel within "pebbles" that migrate through the system during operation and are removed or reinserted into the reactor on a continuous basis. Although gas-cooled reactors can be scaled to high power output, all contemporary designs are constrained to small output (typically 150-300 MWe) to ensure passive removal of the core decay heat. Figure 2 shows a

[123] "Next Generation Nuclear Plant Research and Development Program Plan," Idaho National Laboratory, January 2005.

model of the Modular Helium Reactor (MHR) proposed by General Atomics for the Next Generation Nuclear Plant (NGNP) project.[124]

The R&D needed to realize the benefits of the VHTR include: development and qualification of coated particle fuel, construction materials that can withstand high-temperature, high-temperature/high-pressure heat exchangers, high-temperature sensors, and reactor safety analysis methods for gas-cooled systems. Additionally, alternative coolants are being explored such as liquid fluoride salt, which is largely based on MSR experience gained in the 1960s and 1970s. Although a comprehensive R&D effort was initiated within the Generation IV program, the R&D relevant to helium-cooled reactors is currently funded within the DOE NGNP project, in addition to a cost-shared public/private partnership to construct a commercial scale VHTR. The R&D relevant to fluoride-salt-cooled reactors, which is an advanced option for high-temperature systems, has been resumed recently within the DOE Advanced Reactors Concepts (ARC) program.

[124] "Next Generation Nuclear Plant Conceptual Design Report, INL/EXT-07-12967, Revision 1, November 2007.

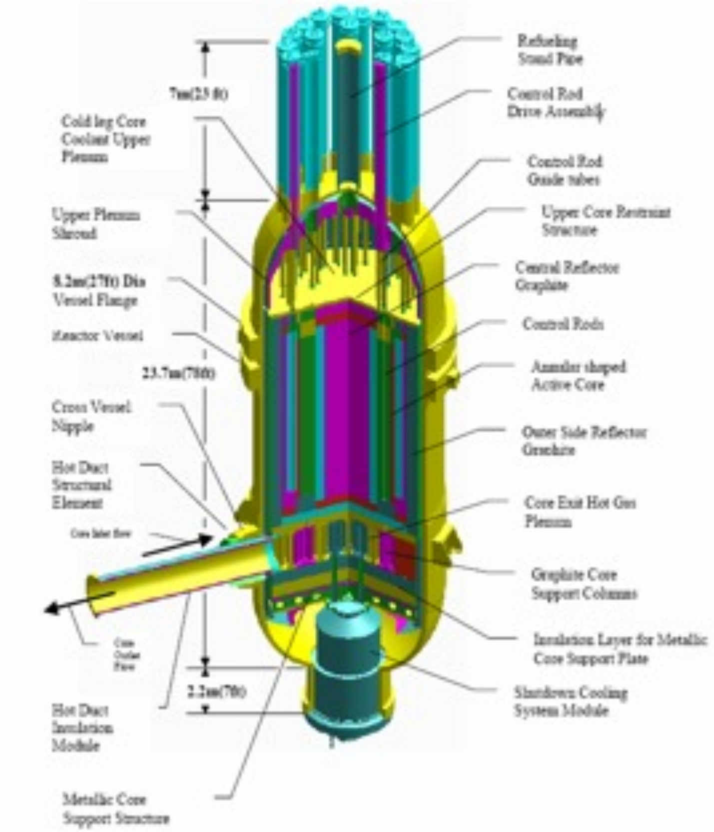


Fig. 2. Model of MHR design for high-temperature process heat applications.

Fast-Spectrum Reactors

The second class of Generation IV reactors addresses the need to manage both nuclear fuel resources and nuclear waste products, which will become increasingly important as the use of nuclear energy is expanded. These functions are best accomplished using fast-spectrum reactor designs because fast-spectrum reactors have the benefit of producing more neutrons beyond what is needed to sustain the fission reaction than do thermal-spectrum reactors. These excess neutrons can be used for a variety of purposes, such as producing new fuel from fertile material; in fact they can produce more fuel than they burn, or they can consume long-lived waste products from used nuclear fuel discharged from other reactors. In order to achieve the excess neutrons, fast-spectrum reactors must not contain low atomic mass materials such as water or graphite that moderate the neutrons to lower energy. Typical coolants used in fast-spectrum reactors include molten sodium, lead or lead-bismuth, and gas. All of these coolants can operate at temperatures higher than water-cooled reactors, typically in the range of 500-700°C.

Sodium, lead and gas-cooled fast spectrum reactors were studied in the United States during the early part of the Generation IV program. Of these, sodium appears to be the most promising, due in part to the more extensive international experience with sodium-cooled reactors. The United States has built and operated three sodium-cooled fast spectrum reactors: the Experimental Breeder Reactors I and II and the Fast Flux Test Facility. Currently, France, Russia, Japan, China, and India have or are pursuing sodium-cooled reactor technology. A challenge for SFRs is the energetic reaction that sodium metal has with water, which requires extra precautions, and hence expense, to avoid sodium-water interactions. This is especially challenging for systems that use the steam Rankine cycle for power conversion, which necessarily requires water in the secondary system. Figure 3 shows a model of a sodium-cooled reactor design being promoted by General Electric-Hitachi (GE-H), designated the Power Reactor Innovative Small Module (PRISM).[125]

The promising development of closed supercritical CO_2 Brayton cycle power conversion systems (a high efficiency thermodynamic cycle used in gas turbines) will help to significantly increase the power conversion efficiency and reduce the sodium-water interaction challenge in SFRs. Examples of other R&D needs for successful commercialization of SFRs include material and fuel development and qualification, and under-sodium viewing technology for inspection and maintenance.

[125] C. E. Boardman, et al, "Optimizing the Size of the Super-PRISM Reactor," *Proceedings of the International Conference on Nuclear Energy* (ICONE) 8, Baltimore, MD, 2000.

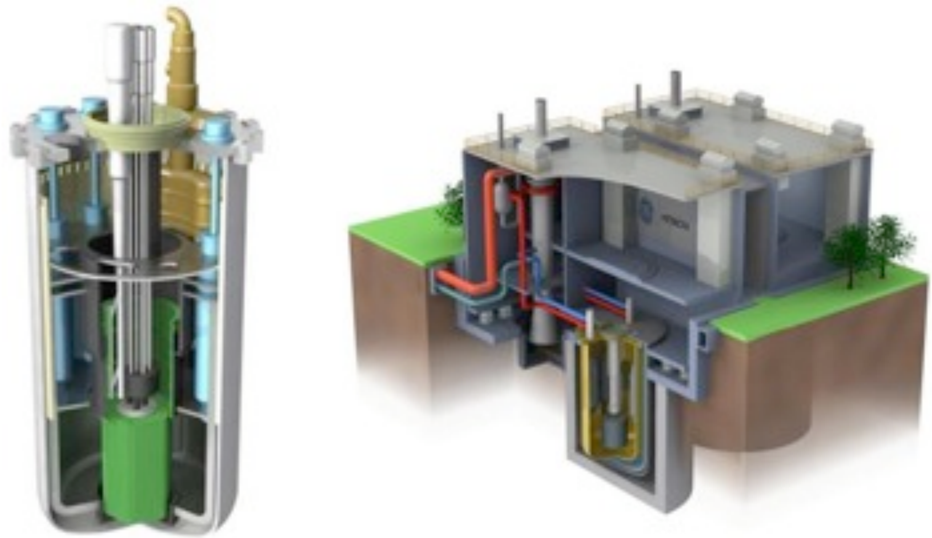


Fig. 3. Model of GE-H PRISM reactor (left) and plant (right).

Small Modular Reactors

Very recently, a third class of advanced reactors has emerged that straddles between the Generation III+ designs and the Generation IV concepts. This is the class of small modular reactors (SMR), which is not a specific reactor technology but rather a special implementation of a technology. SMRs add affordability and flexibility to the other benefits of Generation III and IV systems by reducing the total capital cost of a nuclear plant and enabling more agile plant designs. Although SMR designs for commercial nuclear power first emerged in the late 1970s, no designs have been certified by the NRC, and it has been only in the past few years that vendors and utilities have begun pursuing them actively. Currently, SMRs based on water, helium, sodium, lead, and fluoride salt coolant technologies are being developed by either the commercial industry or by the R&D community. The distinguishing characteristics of SMRs are: their small power output (less than 300 MWe compared to 1100-1600 MWe for the Generation III+ designs), substantial fabrication within a factory environment and then transported and installed on-site, and operation typically in parallel with additional reactor modules to constitute a single power plant.

This "bite-size" implementation of nuclear power offers the owner a number of significant business advantages:

- The power plant can be sized according to the capacity needed by the customer and potentially expanded later if additional capacity is needed.
- The multiplicity of modules improves power availability since for a multi-module plant, maintenance and refueling can be performed on a single module while the other modules continue to operate.
- The lower upfront capital investment and incremental build-out reduces the owner's debt profile and improves financing options because the early units can generate revenue to help finance the construction of later units.

Additionally, a number of technical advantages include:

- Factory fabrication improves quality control, standardization, and schedule reliability while reducing manufacturing cost.
- Individual modules are simpler and more robust due to extensive use of passive safety features.
- Below-grade siting of the smaller reactor enhances safety and security.

The first SMRs likely to be ready for deployment are those based on familiar water-cooled reactor technology. Multiple designs are well underway by both traditional reactor vendors and new upstart companies. One of the most modular SMRs is the NuScale design, which has a power of 45 MWe and a reference plant design consisting of 12 modules (shown in Fig. 4).[126]

A major challenge for the deployment of SMR designs is the licensing process, which must account for several design, operational, and financial differences relative to large plant designs. Many of the regulatory issues have been identified by the NRC and are being addressed by the NRC, SMR vendors and other stakeholder groups such as the Nuclear Energy Institute and the American Nuclear Society.[127] Also, the new

[126] P. Lorenzini, "NuScale Power: Capturing the 'Economies of Small'," presentation at the International Conference on Advances in Nuclear Power Plants 2010, San Diego, CA, June 13-17, 2010.

[127] "Potential Policy, Licensing, and Key Technical Issues for Small Modular Reactor Designs," Nuclear Regulatory Commission, SECY-10-0034, March 28, 2010.

economic model of "economies of small" to replace the more familiar economies of scale are yet unproven. For non-LWR-based SMR designs, the R&D needs are similar to those mentioned above for high-temperature and fast-spectrum reactor designs, for example: the development and qualification of new materials and fuels, advanced instrumentation, and innovative components.

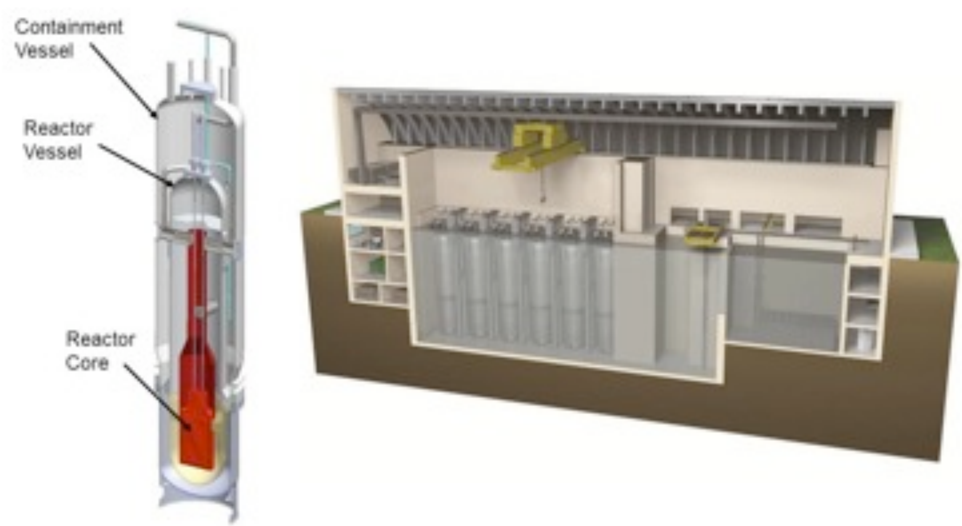


Fig. 4. Model of NuScale reactor and containment vessel (left) and plant (right).

Outlook

The unsurpassed safety and performance record of the current U.S. fleet of nuclear power plants have ensured that large LWRs will continue to be an important cornerstone of the U.S. clean energy portfolio. However, the challenging energy goals of the United States support the need for future generations of reactor designs that can further expand the use of nuclear energy for electricity production and extend the benefits of nuclear energy to non-electrical energy-intensive applications. The plant designs and underlying technologies will need to be different from the current fleet of LWRs, and this will require a commensurate amount of technology R&D and ultimate demonstration of the new technologies and business models for their successful deployment.

While industry is very engaged in the development and eventual deployment of advanced reactor systems, the barriers to deployment are significant and will require government support to overcome both technical and institutional challenges. These challenges range from relatively modest licensing issues to decade-long fuel and materials research and development needs. For the range of advanced systems discussed here, the LWR-based SMR designs are likely to succeed in deployment first due to several factors, including: (1) minimal technical issues needing resolution, (2) proven safety and operational characteristics of water-cooled systems resulting in few licensing issues to industry and NRC, and (3) a rapidly growing customer base of utilities considering SMRs as affordable, incremental capacity or as carbon-free replacements for older, smaller fossil plants. Even for these designs, however, government support and resources are needed to facilitate demonstration of the new engineering, regulatory and business models for first-mover SMRs. An aggressive public/private partnership to deploy the new designs could result in the first commercial plants being ready to operate by 2018-2020.

High-temperature and fast-spectrum reactors, while offering important new functionalities, will likely take longer to achieve commercialization and will require more extensive government support for research and demonstration. In addition to addressing a more extensive list of technical and regulatory challenges, introducing high-temperature reactors to the process heat market requires that the customer base become more familiar and comfortable with the technology. Good progress has been made with the NGNP project, which includes a substantial customer engagement, but the process is relatively new compared to the level of experience of utility customers with water-cooled reactors. Similarly, fast-spectrum reactors face a comparable number of technical and regulatory challenges and an uncertain customer base. Deployment of these advanced systems may be possible by 2025-2030 with appropriate government support and demonstration. Meaningful collaborations with other countries that are also seeking to develop these same technologies will be very important to integrate knowledge and minimize development costs.

In summary, emerging nuclear technologies such as high-temperature, fast-spectrum, and small modular reactors have the ability to offer clean, affordable and abundant energy for the United States and should become key components of the future energy portfolio.

ABOUT THE AUTHORS

John F. Ahearne

Dr. Ahearne is the Director of the Ethics Program at Sigma Xi, The Scientific Research Society, a Lecturer in public policy at Duke University, and an Adjunct Scholar at Resources for the Future. His professional interests are reactor safety, energy issues, resource allocation, and public policy management. He received his B.S. and M.S. degrees from Cornell University and a Ph.D. in physics from Princeton University. He served in the U.S. Air Force from 1959 to 1970, resigning as major. He has also served as Deputy and Principal Deputy Assistant Secretary of Defense (1972-1977), in the White House Energy Office (1977), as Deputy Assistant Secretary of Energy (1977-1978), and as Commissioner and Chairman of the U.S. Nuclear Regulatory Commission (chairman, 1979-1981). He currently serves on the Department of Energy's Nuclear Energy Research Advisory Committee. He is a fellow of the American Physical Society, the Society for Risk Analysis, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences; and a member of the National Academy of Engineering, Sigma Xi, and the American Nuclear Society.

Albert V. Carr, Jr.

Mr. Carr has spent his career in the field of energy law, beginning in 1971 as a Trial Attorney in the Office of General Counsel of the Federal Power Commission, the predecessor agency to the Federal Energy Regulatory Commission. He then took a position as a Trial Attorney in the regulatory division of the Office of General Counsel of the U. S. Atomic Energy Commission, the predecessor agency to the U. S. Nuclear Regulatory Commission. In 1976, he left government service and entered private practice in Washington D. C. In 1981, he joined the Legal Department of Duke Power Company in Charlotte, NC. While at Duke he represented Duke Power and its subsidiaries in a variety of matters related to Federal regulation of the electric utility industry. From 1981 to 1993, he was responsible for, among other things, regulatory matters for Duke's seven nuclear units, including contested licensing proceedings for Duke's Catawba Nuclear Station. In 1998, he retired from full-time employment as Deputy General Counsel, Duke Energy Corporation and continued for several years to represent Duke and other clients in energy regulatory and legislative matters. He has recently participated in several national studies and analyses of, and given presentations on, the potential revival of the domestic nuclear power industry. In the fall of 2000, as an Adjunct Professor of Law at the Washington & Lee University School of Law, he began teaching a course in Federal Energy Regulation. Most recently, he has become Of Counsel with the international law firm Duane Morris LLP, working with the firm's Energy and Construction departments in developing a nuclear licensing practice. Mr. Carr received his BA in English from the Virginia Military Institute in 1966 and his JD from Washington & Lee in 1971. A veteran of the United States Marine Corps, he is a member of the Virginia, North Carolina and District of Columbia Bars.

Harold A. Feiveson

Dr. Feiveson is a Senior Research Scientist and member of Princeton's Program on Science and Global Security of the Woodrow Wilson School of Public and International Affairs. He had co-directed the Program from its inception in 1974 until 2007. His principal research interests are in the fields of nuclear weapons and nuclear energy policy. He was editor and a principal author of the book, *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-alerting of Nuclear Weapons* (Brookings 1999). He has taught regularly in the Woodrow Wilson School for the past 37 years on a range of topics, including on the environment, energy, and nuclear arms control. Before coming to Princeton, he was a member of the Science Bureau of the U.S. Arms Control and Disarmament Agency from 1963 to 1967. He was one of the founders of the international journal, *Science & Global Security,* and editor during the first twenty-one years of the journal, until 2010. He received an M.S. in theoretical physics from the University of California Los Angeles in 1959 and a Ph.D. in public affairs from Princeton University in 1972.

Daniel Ingersoll

Dr. Daniel Ingersoll is a Senior Program Manager for the Nuclear Technology Programs Office at Oak Ridge National Laboratory. He recently served as Campaign Director for the Grid-Appropriate Reactors program within the Global Nuclear Energy Partnership has participated in several advanced reactor programs, including the Advanced High Temperature Reactor project, the International Reactor Innovative and Secure project, and the Space Reactor Technology Program. During his 32 years at ORNL, he led various ORNL research groups and sections dedicated to radiation transport modeling and reactor physics analysis. He received a B.S. degree in physics from Miami University in 1973 and a Ph.D. in nuclear engineering from the University of Illinois in 1977. He is a Fellow of the American Nuclear Society and Past Chairman of the ANS Radiation Protection and Shielding Division.

Andrew C. Klein

Dr. Klein is Professor of Nuclear Engineering and Radiation Health Physics at Oregon State University. Dr. Klein has served as Director of Educational Partnerships at the

Idaho National Laboratory in Idaho Falls, ID, as Head of the Department of Nuclear Engineering and Radiation Health Physics at Oregon State University, and as Director of the Oregon State University Radiation Center. Professor Klein received his B.S. in Nuclear Engineering from Pennsylvania State University in 1977. He completed his M.S. in Nuclear Engineering and his Ph.D., also in Nuclear Engineering, from the University of Wisconsin, Madison in 1979 and 1983 respectively. His research interests are focused on nuclear reactor systems design and analysis including applications in space and fusion energy and nuclear nonproliferation technology. He has been an author on more than 90 technical publications. He is currently a member of the Institute for Nuclear Power Operation's National Nuclear Accrediting Board, the Associate Editor for North America for *Nuclear Technology* and an Advisory Editor for the *Annals of Nuclear Energy* and was a member of the U.S. Department of Energy's Nuclear Energy Research Advisory Committee, NASA's Space Science Advisory Committee, and ABET Inc.'s Engineering Accreditation Commission.

Stephen Maloney

Mr. Maloney is a Partner at Azuolas Risk Advisors. A longtime energy risk analyst in oil, natural gas, LNG and electric power, he also served as a nuclear risk analyst and participated in several accident rulemakings, including station blackout, fire protection/safe shutdown and other severe accidents. He has also consulted on several nuclear power plant M&A transactions, and investment decisions. He was a former commissioned officer in the US Navy's nuclear propulsion program and qualified as Chief Engineer for the C1W reactor. He has an MS Operations Research, BS Physics, and BS Mathematics. He was licensed as a professional engineer and is a member of the Global Association of Risk Professionals, the American Mathematical Society and INFORMS.

Ivan Oelrich

An independent defense analyst, Dr. Oelrich was the former Vice President of the Strategic Security Program at the Federation of American Scientists. Previously, he worked at the Institute for Defense Analyses, Harvard University's Kennedy School of Government, the Office of Technology Assessment, and the Defense Threat Reduction Agency. He has taught as an adjunct professor at Georgetown University and the Johns Hopkins University. He received his B.S. from the University of Chicago and a Ph.D. from Princeton University, both in chemistry. He had a pre-doctoral fellowship at the Lawrence Livermore National Laboratory and later conducted research and taught in the Physics Department of the Technical University of Munich in Germany.

Sharon Squassoni

Ms. Squassoni serves as Director and Senior Fellow of the Proliferation Prevention Program at CSIS. Prior to joining CSIS, she was a Senior Associate in the Nuclear Nonproliferation Program at the Carnegie Endowment for International Peace. From 2002-2007, she advised Congress as a Senior Specialist in weapons of mass destruction at the Congressional Research Service, Library of Congress. Before joining CRS, she worked briefly as a reporter in the Washington bureau of Newsweek magazine. She also served in the executive branch of government from 1992 to 2001. Her last position was Director of Policy Coordination for the Nonproliferation Bureau at the State Department. She also served as a policy planner for the Political-Military Bureau at State. She began her career in the government as a nuclear safeguards expert in the Arms Control and Disarmament Agency. She is the recipient of various service awards and has published widely. She received her B.A. in political science from the State University of New York at Albany, a Masters in Public Management from the University of Maryland, and a Masters in National Security Strategy from the National War College.

Richard Wolfson

Dr. Wolfson is the Benjamin F. Wissler Professor of Physics at Middlebury College, where he also teaches Climate Change in Middlebury's Environmental Studies Program. He completed his undergraduate work at MIT and Swarthmore College, graduating from Swarthmore with a double major in Physics and Philosophy. He holds a master's degree in Environmental Studies from the University of Michigan and a Ph.D. in Physics from Dartmouth. Professor Wolfson's published work encompasses diverse fields such as medical physics, plasma physics, solar energy engineering, electronic circuit design, observational astronomy, theoretical astrophysics, nuclear issues, and climate change. His current research involves the eruptive behavior of the sun's outer atmosphere, or corona, as well as terrestrial climate change and the sun–Earth connection. He is the author of several books, including the college textbooks *Physics for Scientists and Engineers*, *Essential University Physics*, and *Energy, Environment, and Climate*. He is also an interpreter of science for the nonspecialist, a contributor to *Scientific American*, and author of the books *Nuclear Choices: A Citizen's Guide to Nuclear Technology* and *Simply Einstein: Relativity Demystified*.

EDITORS

Charles D. Ferguson

Dr. Charles D. Ferguson is the President of the Federation of American Scientists (FAS). Prior to FAS, he worked as the Philip D. Reed Senior Fellow for Science and Technology at the Council on Foreign Relations. 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). While working at the Monterey Institute, he was the lead author of the 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. Dr. Ferguson has consulted with Sandia National Laboratories and the National Nuclear Security Administration on improving the security of radioactive sources. He has worked as a physical scientist in the Office of the Senior Coordinator for Nuclear Safety at the U.S. Department of State. He has recently completed the book *Nuclear Energy: What Everyone Needs to Know* (Oxford University Press, May 2011). He graduated with distinction from the United States Naval Academy, served in the U.S. nuclear Navy, and earned a Ph.D. in physics from Boston University.

Frank A. Settle

Dr. Frank Settle received a BS from Emory and Henry College and a PhD in chemistry from the University of Tennessee. Since retiring as professor of chemistry at VMI in 1992, he has been a program officer at the National Science Foundation, a consultant for the Department of Energy, and is currently a visiting professor at Washington and Lee University where he directs the Alsos Digital Library for Nuclear Issues. He has taught courses on nuclear history, nuclear energy, and weapons of mass destruction since 1991.

FEDERATION of AMERICAN SCIENTISTS and WASHINGTON AND LEE UNIVERSITY

Federation of American Scientists
1725 DeSales Street, NW, 6th Floor
Washington, DC 20036
TEL 202-546-3300 FAX 202-675-1010

www.FAS.org

Washington and Lee University
204 West Washington Street
Lexington, VA 24450-2116
TEL 540-458-8400

www.WLU.edu

$15.00
ISBN 978-1-938187-00-1
51500>
9 781938 187001