Nuclear Reactors: Generation to Generation

Stephen M. Goldberg and Robert Rosner

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Cover image: A photo taken on October 31, 2010, that shows the construction site of the Fuqing nuclear power station project in Fuqing, southeast China's Fujian Province.
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Preface

The devastating earthquake, tsunami, and consequent multi-reactor damage in Japan will have a significant impact on the future use of nuclear energy, the nuclear industry, and the global nuclear order. The full impact will not be known for some time. Data about the incident unfolding at the Fukushima Daiichi nuclear power reactors were still being compiled when this paper went to press.

To make wise choices about the future of nuclear power, we need improved knowledge of the safety, safeguards, and security features of both existing and new nuclear energy plants. Understanding the potential advantages and disadvantages of nuclear energy is critical for those stakeholders and decision-makers facing national energy challenges. This publication provides an overview of the evolution of nuclear reactor technology and discusses six important factors in the development and deployment of new reactors.

For over five decades, the American Academy of Arts and Sciences has played an integral role in nonproliferation studies, beginning with a special issue of *Daedalus* on "Arms Control" published in 1960 and continuing with studies conducted by the Academy's Committee on International Security Studies (CISS). More recently, the Academy's Global Nuclear Future (GNF) Initiative—under the guidance of CISS—is examining the safety, security, and nonproliferation implications of the global spread of nuclear energy. The GNF Initiative is promoting innovative scholarship, fostering creative behind-the-scenes interactions with international leaders and stakeholders, examining issues critical to a safer and more secure nuclear future, and developing pragmatic recommendations for managing the emerging nuclear order. The GNF Initiative is supported in part by grants from The Carnegie Corporation of New York, the William and Flora Hewlett Foundation, and the Alfred P. Sloan Foundation.

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Many factors influence the development and deployment of nuclear reactors. In this white paper, we identify six of them: cost-effectiveness, safety, security and nonproliferation features, grid appropriateness, commercialization roadmap (including constructability and licensability), and management of the fuel cycle. We also outline the evolution of nuclear reactor generations and describe current and possible future reactor proposals in light of these six key factors. In our opinion, incorporation of passive safety features and implementation of dry cask storage for used fuel reasonably address future safety and waste concerns. The nonproliferation benefits of future designs remain unclear, however, and more research will be required. Investment barriers have been overcome in different ways by different countries, but identifying investment priorities and investors will determine, in general, the extent to which nuclear power remains a viable wedge of the global energy future. Geopolitical factors may tip the scales in favor of a country investing in nuclear energy. These factors include the obvious hedging strategies (i.e., using nuclear power as a hedge against an uncertain natural gas supply and price outlook, as well as an uncertain climate policy), as well as more-subtle strategies, such as using nuclear power to demonstrate technological prowess or as a future bargaining chip in a security context. The lessons from the unfortunate events in Japan were still being assessed when this paper went to press. What is clear, however, is that U.S. leadership is required.

THE KEY REACTOR FACTORS

Nuclear reactor designs are usually categorized by "generation"; that is, Generation I, II, III, III+, and IV. The key attributes characterizing the development and deployment of nuclear power reactors illuminate the essential differences between the various generations of reactors. The present analysis of existing reactor concepts focuses on six key reactor attributes:

1. *Cost-effectiveness.* From the customer's perspective, a nuclear kilowatt-hour is, aside from its cost, indistinguishable from a renewable or fossil-fired kilowatt-hour. Nuclear power must therefore be economically competitive. Accounting for the life-cycle costs actually paid by the retail electricity customer has proven to be far from trivial

and is one of the more controversial elements in the discussion of competing energy technologies. Fossil-fired power, without carbon controls, sets the market price today and will likely continue to do so over the next decade. What policies or initiatives might make nuclear power more competitive with current fossil fuel prices? How can the prospects for nuclear power plant financing be improved?

2. *Safety.* Several nuclear systems are incorporating passive design features to ensure the safe operation of nuclear reactors, as compared to active safety systems requiring intervention by human agents. This is due to a variety of technical and public policy reasons, including quantitative risk reductions. What safety measures are proposed for new reactors? Do they maintain or advance current measures?

3. *Security and nonproliferation.* Nuclear power systems must minimize the risks of nuclear theft and terrorism. Designs that will play on the international market must also minimize the risks of state-sponsored nuclear weapons proliferation. Concerns about dual-use technologies (i.e., technologies that were originally developed for military or other purposes and are now in commercial use) are amplifying this threat. What designs might mitigate these risks?

4. *Grid appropriateness.* The capabilities of both the local and national electric grid must match the electric power a proposed reactor will deliver to the grid. Grid appropriateness is determined by a combination of nameplate capacity and externalities defined by the extant electrical grid.[1] How does the capacity of the electric grid impact the financial requirements, long-term economic feasibility, and availability of a reactor?

5. *Commercialization roadmap.* Historically, the displacement of a base power source by an alternative source has been an evolutionary process rather than a sudden, disruptive, and radical shift. Attempting to "push the envelope" by forcing the shift is typically economically infeasible because investors are rarely willing to bear, for example, the capital costs associated with the deployment of alternative technology into the existing grid architecture. Commercialization roadmaps must therefore include a plausible timeline for deployment. The current need for near-term readiness (especially in emerging technological powerhouses such as China, India, and the Republic of Korea) is such that only those technologies that have either already been tested

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[1] Some of the externalities include: (1) remote areas requiring localized power centers to avoid long and expensive transmission lines; (2) geography and demography constraints that are best suited to low- and mid-size urban and power needing areas fairly scattered, rather than concentrated in a few "mega centers" and; (3) financial capabilities that preclude raising the several billions dollars capital investment required by larger plants.

in the marketplace or are close to commercial demonstration are likely to be considered. Will modular construction practices streamline the commercialization of nuclear reactors and reduce the overnight cost burden?

6. *The fuel cycle*. The details of a given reactor's fuel cycle are critical elements in determining risk levels for nuclear safety, security, and surety. With both the front and back ends of the fuel cycle, intrinsic properties of reactor design couple intimately with externalities such as the possible internationalization of the front and back end processes.
    a. *The front end*. The extent to which a nuclear reactor requires continued refueling with enriched fresh fuel is a critical factor in determining risk. A related factor is the extent and manner in which the fuel supply (especially its enrichment and fabrication) is internationalized. Moving toward reactor design features—such as high fuel utilization and higher fuel burnup (a measure of how much energy is extracted from fresh fuel; e.g., deep burn reactor designs are generally ≥ 20 percent) and sealed long-life core designs—could significantly reduce such risks.
    b. *Used fuel disposition (the "back end")*. Given the institutional challenges presented by the long-term storage and ultimate disposal of used fuel, future reactor systems must minimize the amount and toxicity of *nuclear waste*. This is an institutional issue, not a short- or intermediate-term safety or security issue. The use of dry cask storage (typically steel cylinders)—a proven, safe approach to storing waste—will provide a 60–80 year window of opportunity in which to conduct a robust, innovative research and development program on an advanced fuel cycle system.

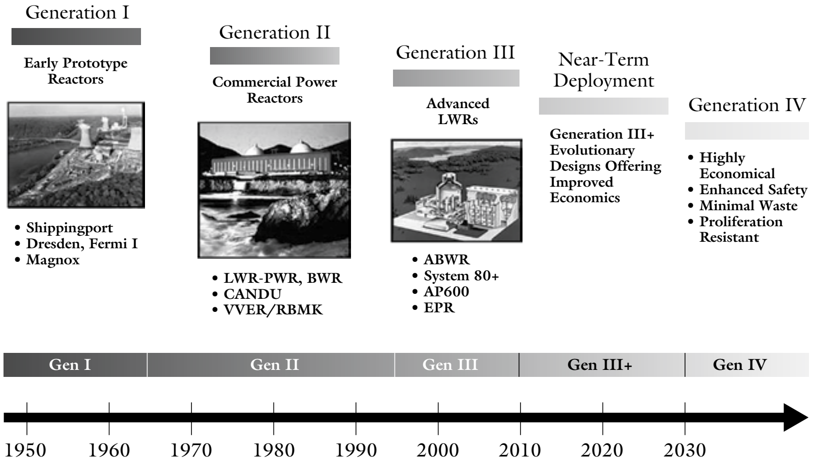
THE HISTORY OF REACTOR GENERATIONS

Three generations of nuclear power systems, derived from designs originally developed for naval use beginning in the late 1940s, are operating worldwide today (Figure 1).

Generation I

Gen I refers to the prototype and power reactors that launched civil nuclear power. This generation consists of early prototype reactors from the 1950s and 1960s, such as Shippingport (1957–1982) in Pennsylvania, Dresden-1 (1960–1978) in Illinois, and Calder Hall-1 (1956–2003) in the United Kingdom. This kind of reactor typically ran at power levels that were

Figure 1. The Evolution of Nuclear Power



Reprinted from U.S. Department of Energy, Office of Nuclear Energy, “Generation IV Nuclear Energy Systems: Program Overview” (Department of Energy, n.d.), http://nuclear.energy.gov/genIV/neGenIV1.html.

“proof-of-concept.” In the United States, Gen I reactors are regulated by the Nuclear Regulatory Commission (NRC) pursuant to Title 10, Code of Federal Regulations, Part 50 (10 CFR Part 50).

The only remaining commercial Gen I plant, the Wylfa Nuclear Power Station in Wales, was scheduled for closure in 2010. However, the UK Nuclear Decommissioning Authority announced in October 2010 that the Wylfa Nuclear Power Station will operate up to December 2012.

Generation II

Gen II refers to a class of commercial reactors designed to be economical and reliable. Designed for a typical operational lifetime of 40 years,[2] prototypical Gen II reactors include pressurized water reactors (PWR), CANada Deuterium Uranium reactors (CANDU), boiling water reactors (BWR), advanced gas-cooled reactors (AGR), and Vodo-Vodyanoi Energetichesky Reactors (VVER). Gen II reactors in the United States are regulated by the NRC pursuant to 10 CFR Part 50.

Gen II systems began operation in the late 1960s and comprise the bulk of the world’s 400+ commercial PWRs and BWRs. These reactors, typically referred to as light water reactors (LWRs), use traditional active safety features involving electrical or mechanical operations that are initiated automatically

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[2] The frequency of core damage to Gen II reactors is reported to be as high as one core damage event for every 100,000 years of operation (10^{-5} core damage events per reactor year for the BWR(4)). In light of the ongoing events at the nuclear power plants in Fukushima, Yamato Province, Japan, the authors strongly suggest that the core damage frequencies be reanalyzed.

and, in many cases, can be initiated by the operators of the nuclear reactors. Some engineered systems still operate passively (for example, using pressure relief valves) and function without operator control or loss of auxiliary power. Most of the Gen II plants still in operation in the West were manufactured by one of three companies: Westinghouse,[3] Framatome[4] (now part of AREVA[5]), and General Electric (GE).

The Korean Standard Nuclear Power Plant (KSNP), which is based on Gen II technology developed by Combustion Engineering (now Westinghouse) and Framatome (now AREVA), is now recognized as a Gen II design and has evolved to become the KSNP+. In 2005 the KSNP/KSNP+ was rebranded as the OPR-1000 (Optimized Power Reactor) for Asian markets, particularly Indonesia and Vietnam. Six OPR-1000 units are in operation, and four are under construction. China's existing and planned civilian power fleet is based on the PWR. Two important designs used in China are the improved Chinese PWR 1000 (the CPR-1000), which is based on Framatome's 900 megawatt (MW) three-loop Gen II design, and the standard PWR 600 MW and 1,000 MW designs (the CNP series).

Table 1. Global Nuclear Power Plant Construction

Reactor designs	China	France	Japan	Republic of Korea	Russia	Other Countries	Total GW
Gen II							
CPR-1000 (Gen II)	18						19.4
CNP series (Gen II)	3						2.0
OPR-1000 (Gen II)				4			4.0
VVER series (Gen II)					7	4	12.3
Gen III							
APR-1400 (Gen III)*				2			2.7
ABWR (Gen III)			2			2	5.4
APWR (Gen III)			2				3.1
Gen III +							
AP-1000 (Gen III+)†	4						4.8
EPR (Gen III+)	2	1				1	6.6
Sub-total	27	1	4	6	7	7	
Total							60.3

* The United Arab Emirates has ordered four APR-1400 reactors.

† The table does not include four U.S. AP-1000 reactor projects. Construction is underway in the United States at the Vogtle sites, and preparation is underway at the Virgil C Summer sites.

Modified from: S&P Credit Research, *Global Nuclear Power Development Offers Lessons for New U.S. Construction* (New York: Standard & Poor's, 2010).

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3. Combustion Engineering is now part of Westinghouse. Toshiba is the majority owner of Westinghouse.

4. BSW's 177 class reactors were sold to Framatome.

5. The parent company, incorporated under French law, is a Société Anonyme (S.A.).

These designs require relatively large electrical grids, have a defined safety envelope based on Western safety standards, and produce significant quantities of used fuel that require ultimate disposition in a high-level waste repository or reprocessing as part of a partially or fully closed fuel cycle. The economics of existing Gen II plants and of those under construction or in the planning stage are generally favorable, particularly in Asia (Table 1 shows a schedule of plants under construction as of November 2010).[6]

The extraordinary events unfolding at the Fukushima Daiichi and Daini nuclear power plants are being assessed by the technical and regulatory experts both in the United States and across the world. At press time, a full assessment is not possible. We have learned that an increased safety focus will likely be required and, at a minimum, will focus on four safety systems: 1) Mark I BWR containment structures; 2) common-mode emergency core cooling capability resulting from loss of emergency backup power; 3) the performance of mixed-oxide fuel in Gen II reactor designs; and 4) critical safety analyses of the various extant used fuel cooling pool designs.

Generation III

Gen III nuclear reactors are essentially Gen II reactors with evolutionary, state-of-the-art design improvements.[7] These improvements are in the areas of fuel technology, thermal efficiency, modularized construction, safety systems (especially the use of passive rather than active systems), and standardized design.[8] Improvements in Gen III reactor technology have aimed at a longer operational life, typically 60 years of operation, potentially to greatly exceed 60 years, prior to complete overhaul and reactor pressure vessel replacement. Confirmatory research to investigate nuclear plant aging beyond 60 years is needed to allow these reactors to operate over such extended lifetimes. Unlike Gen I and Gen II reactors, Gen III reactors are regulated by NRC regulations based on 10 CFR Part 52.[9]

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6. In the United States, early movers will need government assistance, particularly loan guarantees.

7. Core damage frequencies for Gen III and Gen III+ reactors are reported to be lower than those of Gen II reactors, in the range of one core damage event for every 15–20 million years of operation (6×10^{-7} core damage events per reactor year) for the EPR and one core damage event for every 300–350 million years of operation (3×10^{-8} core damage events per reactor year) for the ESBWR. In light of the ongoing events at the nuclear power plants in Fukushima, Yamoto Province, Japan, the authors strongly suggest that these core damage frequencies be reanalyzed.

8. These standardized designs are intended to reduce maintenance and capital costs. The capital cost requirements are highly dependent on country and international material, labor, and other considerations.

9. Following passage of the Energy Policy Act of 1992, the NRC adopted an additional licensing pathway option: the combined construction and operating license (COL). Except for the licensing of Brown's Ferry I and, potentially, a small modular reactor construction application at the TVA Clinch River site, all recent licensing applicants have chosen this pathway, which is seen as a streamlined approach (see Table 2).

The Westinghouse 600 MW advanced PWR (AP-600) was one of the first Gen III reactor designs. On a parallel track, GE Nuclear Energy designed the Advanced Boiling Water Reactor (ABWR) and obtained a design certification from the NRC. The first of these units went online in Japan in 1996. Other Gen III reactor designs include the Enhanced CANDU 6, which was developed by Atomic Energy of Canada Limited (AECL); and System 80+, a Combustion Engineering design.[10]

Only four Gen III reactors, all ABWRs, are in operation today. No Gen III plants are in service in the United States.

Hitachi carefully honed its construction processes during the building of the Japanese ABWRs. For example, the company broke ground on Kashiwazaki-Kariwa Unit 7 on July 1, 1993. The unit went critical on November 1, 1996, and began commercial operation on July 2, 1997—four years and a day after the first shovel of dirt was turned. If the U.S. nuclear power industry can learn from Hitachi's construction techniques, many billions of dollars and years of time might be saved.[11] The Shaw Group and Westinghouse have adopted modular construction practices in launching a joint venture for a Lake Charles, Louisiana, facility that will manufacture modules for the AP-1000.

Generation III+

Gen III+ reactor designs are an evolutionary development of Gen III reactors, offering significant improvements in safety over Gen III reactor designs certified by the NRC in the 1990s. In the United States, Gen III+ designs must be certified by the NRC pursuant to 10 CFR Part 52.

Examples of Gen III+ designs include:

- VVER-1200/392M Reactor of the AES-2006 type
- Advanced CANDU Reactor (ACR-1000)
- AP1000: based on the AP600, with increased power output
- European Pressurized Reactor (EPR): evolutionary descendant of the Framatome N4 and Siemens Power Generation Division KONVOI reactors
- Economic Simplified Boiling Water Reactor (ESBWR): based on the ABWR
- APR-1400: an advanced PWR design evolved from the U.S. System 80+, originally known as the Korean Next Generation Reactor (KNGR)
- EU-ABWR: based on the ABWR, with increased power output and compliance with EU safety standards

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[10] ABB Group's nuclear power business, formerly Combustion Engineering (CE), was purchased by BNFL and merged into Westinghouse Electric Company.

[11] Institutional and regulatory differences between the Japanese and U.S. systems may mitigate some of these savings.

- Advanced PWR (APWR): designed by Mitsubishi Heavy Industries (MHI)[12]
- ATMEA I: a 1,000–1,160 MW PWR, the result of a collaboration between MHI and AREVA.[13]

Manufacturers began development of Gen III+ systems in the 1990s by building on the operating experience of the American, Japanese, and Western European LWR fleets. Perhaps the most significant improvement of Gen III+ systems over second-generation designs is the incorporation in some designs of passive safety features that do not require active controls or operator intervention but instead rely on gravity or natural convection to mitigate the impact of abnormal events. The inclusion of passive safety features, among other improvements, may help expedite the reactor certification review process and thus shorten construction schedules.[14] These reactors, once on line, are expected to achieve higher fuel burnup than their evolutionary predecessors (thus reducing fuel consumption and waste production). More than two dozen Gen III+ reactors based on five technologies are planned for the United States (Table 2 lists applications and their status as of November 2010).

Table 2. New Nuclear Power Plant Applications

Company	Design	Site under Construction	Existing Unit(s)	Existing Plant Design	Operating Plant Design[15]	State	Status
Applications accepted and docketed							
Ameren UE	US-EPR	Callaway (1 unit)	1 Operating	PWR	Westing-house 4 loop, 1,235 MWe	MO	Vendor change to AREVA from Westinghouse for new unit. The company suspended its plan to build a new reactor on April 23, 2009. The NRC suspended review of the combined operating license in June 2009.
Detroit Edison Co.	ESBWR	Enrico Fermi (1 unit)	1 Operating	BWR	GE, Type 4, 1,039 MWe	MI	The only ESBWR application currently open.
Dominion Resources Inc.	APWR	North Anna (1 unit)	2 Operating	PWR	Westing-house, 3 loop, 925 MWe and 917MWe	VA	Originally chose the ESBWR design. On May 7, 2010, Dominion said that it had selected Mitsubishi's US-APWR design and will decide over the next year whether to build the 1,700 MW APWR unit.

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12. The US-APWR is designed to be 1,700 MW because of longer (4.3m) fuel assemblies, higher thermal efficiency (39 percent), and a 24-month refueling cycle. In March 2008, MHI submitted the same design for EUR certification and partnered with Iberdrola Engineering and Construction to build these plants in the EU.

13. ATMEA I is one of the three technologies Jordan is considering for its next power plant.

14. Because no COL has been issued to date, this is an opinion of the authors and might not be shared by nuclear manufacturers of active nuclear safety systems. COL, as defined by the Code of Federal Regulations, means a combined construction permit and operating license with conditions for a nuclear power facility.

15. Net Capacity (MWe) is electricity generated and sold.

Company	Design	Site under Construction	Existing Unit(s)	Existing Plant Design	Operating Plant Design[15]	State	Status
Duke Energy Corp.	AP-1000	William States Lee III Nuclear Station (2 units)	Greenfield[16]	NA		SC	
Entergy Corp.	ESBWR	River Bend (1 unit)	1 Operating	BWR	GE, Type 6, 936 MWe	LA	On Jan. 9, 2009, Entergy requested the NRC to suspend the review of its combined operating license because the company is considering alternate reactor technologies.
Florida Power & Light Co.	AP-1000	Turkey Point (2 units)	2 Operating	PWR	Westinghouse, 3 loop, 693 MWe each	FL	New units delayed from 2018–2020 to 2023. Uprating existing nuclear units
Luminant Power	US-APWR	Comanche Peak (2 units)	2 Operating	PWR	Westinghouse, 4 loop, 1,150 MWe each	TX	PWR technology. Vendor changed from Westinghouse to MHI.
NRG Energy Inc.	ABWR	South Texas Project (STP) (2 units)	2 Operating	PWR	Westinghouse, 4 loop, 1,168 MWe each	TX	Existing site has a PWR. The new unit is an ABWR.
NuStart Energy[17] (Tennessee Valley Authority [TVA])	AP-1000	Bellefonte (2 units)	Greenfield	NA		AL	TVA staff has said that completing the 1,260 MW Bellefonte Unit 1 is preferable to building an AP-1000 unit. When stopped in 1988, Unit 1 was 88% complete, and Unit 2 was 58% complete. Over the years, equipment from these sites has been used elsewhere; therefore the percentage complete needs to be revised downward.
NuStart Energy	ESBWR	Grand Gulf (1 unit)	1 Operating	BWR	GE, Type 6, 1,204 MWe	MS	On Jan. 9, 2009, NRC was requested to suspend the review of its combined operating license because the company is considering alternate reactor technologies.
PP&L Generation	US-EPR	Bell Bend[18] (1 unit)	2 Operating	BWR	GE, Type 4, 1,100 MWe and 1,103 MWe	PA	The original units are BWRs. The EPR is a PWR. Vendor changed to AREVA from GE. Although the application is open, the company will decide in 2011–2012 whether it plans to pursue construction of a new plant.

16. Undeveloped (virgin) site earmarked for potential new nuclear reactor.

17. NuStart Energy is a limited liability corporation comprised of ten power companies, created in 2004 for the dual purposes of: 1) obtaining a Construction and Operating License (COL) from the Nuclear Regulatory Commission (NRC), using the never before used, streamlined licensing process developed in 1992 and 2) completing the design engineering for the selected reactor technologies.

18. New site adjacent to PPL's Susquehanna Steam Electric Station, Luzerne County, PA.

Company	Design	Site under Construction	Existing Unit(s)	Existing Plant Design	Operating Plant Design[15]	State	Status
Progress Energy Inc.	AP-1000	Levy County (2 units)	Greenfield	NA		FL	In May 2010, Progress announced plans to slow work at Levy to reduce capital spending and avoid short-term rate increases and because of a delay in the licensing timeline for its combined operating license, as well as the current economic climate and uncertainty about U.S. energy policy.
Progress Energy Inc.	AP-1000	Shearon Harris (2 units)	1 Operating	PWR	Westinghouse 3 loop, 860 MWe	NC	
South Carolina Electric & Gas Co.	AP-1000	Virgil C Summer (2 units)	1 Operating	PWR	Westinghouse, 3 loop, 885 MWe	SC	
Southern Nuclear Operating Co.	AP-1000	Vogtle (2 units)	2 Operating	PWR	Westinghouse, 4 loop, 1,150 MWe each	GA	An $8.3 billion conditional loan guarantee was received Feb. 16, 2010.
Tennessee Valley Authority	mPower	Clinch River	Greenfield			TN	TVA has announced its intention to submit a Construction Permit Application in 2012. As many as 6 mPower units are planned.
Unistar	US-EPR	Calvert Cliffs (1 unit)	2 Operating	PWR	Combustion Engineering, 825 MWe each	MD	Vendor change to AREVA (Combustion Engineering was acquired by Westinghouse in 2000).
Unistar	US-EPR	Nile Mile Point (1 unit)	2 Operating	BWR	GE, Type 2: 610MWe and Type 5:1143 MWe	NY	On Dec. 7, 2009, Unistar requested the NRC to temporarily suspend Nile Mile Point's combined operating license application.
Unannounced technology (not submitted)							
Alternate Energy Holdings	Undecided	Payette (1 unit)	Greenfield	NA		ID	
Blue Castle Project	Undecided	Blue Castle	Greenfield			UT	
Exelon Corp.	ABWR	Victoria County (2 units)	Greenfield	NA		TX	Exelon originally selected the ESBWR design and then switched to ABWR. In July 2009, the company changed its combined operating license to an early site permit application that was submitted to the NRC on March 25, 2010.

Company	Design	Site under Construction	Existing Unit(s)	Existing Plant Design	Operating Plant Design[15]	State	Status
PSEG Inc.	Undecided	Salem County	3 operating	BWR & PWR	Westinghouse PWR (Salem): 1,106 MWe each BWR (Hope Creek): 1,031 MWe	NJ	On May 25, 2010, PSEG filed an early site permit with the NRC. Location will be contiguous to the Salem and Hope Creek units in Salem County.

Based upon Aneesh Prabhu, "The Expansion of Nuclear Power Plants in the U.S.: What Could Get in the Way?" in S&P's Special Reports: Can the U.S. Nuclear Power Industry Hold Its Spot as the World Leader? (New York: Standard & Poor's, 2010). Modified and updated with information found at http://world-nuclear.org/NuclearDatabase/Default.aspx?id=27232 (accessed on February 11, 2011).

Gen III and III+ designs have a defined safety envelope based on Western safety standards and set the worldwide standards for safeguards and security. However, they have also produced a legacy of significant quantities of used fuel, require relatively large electric grids, and present public-acceptance challenges.

NEXT STEPS

After enduring the usual reliability growing pains, Gen I and Gen II nuclear reactors have proven to be economically successful. According to the Nuclear Energy Institute, U.S. nuclear power plants in 2006 supplied the second-highest amount of electricity in the industry's history while achieving a record-low average production cost of 1.66 cents/kWh. Because the capital costs of many Gen I and Gen II reactors have been paid off, average production costs have been below 2 cents/kWh for the past seven years. Capacity factors have remained higher than 90 percent. Self-financing (essentially paid off the balance sheet) is a key factor, leading to not having to pay any capital charges and resulting in very low costs to operate these plants. Power upgrades and improvements in operational efficiency over the past decade have yielded the equivalent of multiple new nuclear plants. Whether this performance platform can be extrapolated to the Gen III and III+ designs is uncertain[19] because of the significant overnight cost[20] investment for the GEN III/III+ plants.

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[19] The ratings agencies have continually downgraded new nuclear investments, until there is an operating history for these new plants.

[20] The overnight cost of a large capital project is the cost of the project (i.e., all capital costs, including owner's costs) without financing costs, as if the project could be completed overnight.

The Move to Small Modular Reactors

As President Barack Obama pushes to revive the domestic nuclear power industry amid mounting concerns about fossil-fired electricity generation, a new type of small reactor is about to enter the market. Several firms are working on Gen III and Gen III+ designs that are smaller in scale than the current designs and in several cases also make use of modular construction techniques. This small modular reactor (SMR) architecture is based on significant learning-by-doing efficiencies. The vendors are planning to apply for NRC design certification pursuant to either 10 CFR Part 50 or 10 CFR Part 52. It is our understanding that because of new policy issues (e.g., revised emergency planning zone and accident scenarios) updated or new regulatory criteria and guides may be necessary. One example of SMR architecture is the mPower 125 MW module (Figure 2), an integral, advanced LWR of modular design, in current development through an alliance of Babcock and Wilcox Nuclear Energy Inc. (B&W NE) and Bechtel Power Corporation. The reactor is significantly smaller than most operating PWRs but is scalable and incorporates already existing LWR technology, a fully passive safety design, industry-standard PWR fuel, 60-year used fuel storage, and a four-to-five-year refueling cycle. The small B&W NE reactor is 75 feet tall and 15 feet wide. Unlike steam generators in traditional nuclear facilities, its steam generator (the cylindrical structure seen along the center axis of the reactor vessel in Figure 2) is integrated within the reactor vessel.

Other notable examples include a 45 MW integral, scalable, modular LWR currently in development by NuScale Power; and the International Reactor Innovative and Secure (IRIS), a 300 MW scalable, modular LWR reactor developed by an international consortium led by Westinghouse.[21] The design for NuScale Power's LWR calls for advanced passive safety features and for the entire nuclear steam supply system to be prefabricated and sited below ground.[22]

These new reactors—smaller than a rail car and one-tenth the cost of a big plant—could be built quickly and installed at the dozens of existing nuclear sites, or they could replace existing coal-fired plants that do not meet current federal air quality emission standards. "We see significant benefits from the new, modular technology," said Donald Moul, vice president of nuclear support for First Energy, an Ohio-based utility corporation.[23]

Smaller reactors (defined by the International Atomic Energy Agency as those capable of generating less than 300 MW) are the logical choice for smaller countries or countries with a limited electrical grid. Small reactors are

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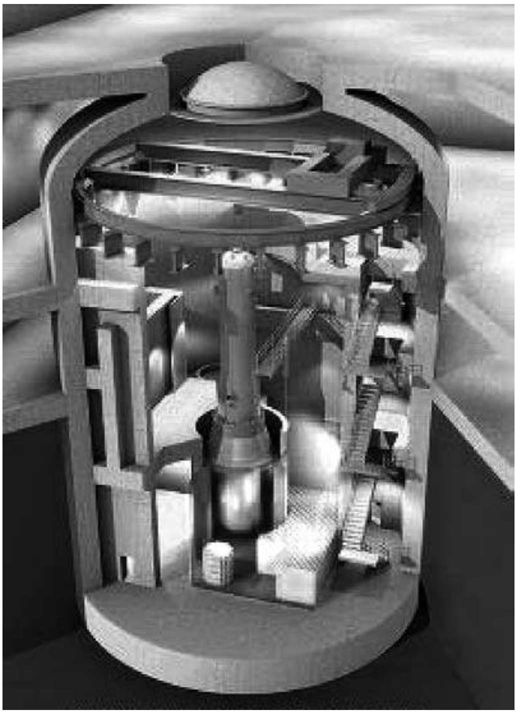
[21] Westinghouse plans to announce details of a new design evolved from the IRIS design.

[22] At the time of release of this paper, NuScale Power abruptly halted its operations after the U.S. Securities and Exchange Commission began a civil action against the Michael Kenwood Group, the main investor in the company.

[23] "Small Reactors Generate Big Hopes," http://online.wsj.com/article/SB10001424052748703444804575071402124482176.html.

Figure 2. The Babcock and Wilcox mPower Reactor



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now in different stages of development throughout the world. They are attractive because of their simplicity and enhanced safety and because of the relatively limited financial resources required to build them. But acclaim is not universal. Detractors argue that SMR designs are not economical because of economies of scale. Capital construction costs (price per one thousand watts of electric capacity, or $/kWe) of a nuclear reactor decrease with size, but the economy of scale applies only if reactors are of a very similar design, as has historically been the case. The design characteristics of SMRs, however, are significantly different from those of large reactors. SMRs approach the economies of scale problem by achieving significant cost savings elsewhere. For example, SMR designs seek to streamline safety and safeguard requirements by replacing (at least some) security guards with concrete security barriers and/or by building underground, streamlining the requirements for operators, and streamlining emergency planning zone requirements. Awareness and realization of the economic potential of small, modular reactors have grown significantly in the last few years. Argonne National Laboratory (ANL) is conducting a significant, detailed economic analysis that will address the economic competitiveness of these reactors.

What these designs might not do, however, because of deep-seated American Society of Mechanical Engineers In-service Inspection (ISI) and Nondestructive Engineering Division (NDE) requirements, is to stretch out the refueling schedule over decades. The new designs do stretch out refueling schedules, from 18 months to possibly 3–5 years and potentially to as long as 10 years (subject to ISI testing and monitoring). But longer-term refueling cycles (such as are commonly associated with so-called battery reactors) are currently left to the future. The following is a list of SMRs being researched and/or developed in the United States:

- *Water-cooled reactors with small coated particle fuel without on-site refueling:* AFPR (PNNL)
- *Sodium-cooled small reactor with extended fuel cycles:* 4S (Westinghouse/Toshiba); PRISM (GE); ARC (ARC)
- *Lead- or lead-bismuth-cooled small reactors with extended fuel cycles:* HPM (Hyperion); LFR/SSTAR and its variations such as STAR-LM, STAR-H2, and SSTAR (ANL, LLNL and LANL); ENHS (UC Berkeley)
- *Gas-cooled thermal neutron spectrum reactor:* MHR (GA); PBMR (Westinghouse); ANTARES (AREVA-U.S.)
- *Gas-cooled fast neutron spectrum reactor with extended fuel cycle:* EM2 (GA)
- *Salt-cooled small reactor with pebble-bed fuel:* PB-AHTR (UC Berkeley); SmAHTR (ORNL).

Looking Past Gen III and Gen III+

Nuclear scientists have left implementation of the Gen III+ and SMR designs to the engineers, believing them to be within the current state-of-the-art, and have instead focused on nuclear alternatives—commonly called Gen IV—that still require considerable fundamental research.

Conceptually, Gen IV reactors have all of the features of Gen III+ units, as well as the ability, when operating at high temperature, to support economical hydrogen production, thermal energy off-taking, and perhaps even water desalination. In addition, these designs include advanced actinide management.[24]

Gen IV reactors include:

- High temperature water-, gas-, and liquid salt–based pebble bed thermal and epithermal reactors.

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[24] An actinide is an element with an atomic number from 89 (actinium) to 103 (lawrencium). The term is usually applied to elements heavier than uranium. Actinides typically have relatively long half-lives. Plutonium and the minor actinides (plutonium and uranium are the "major" actinides) will be largely responsible for the bulk of the radiotoxicity and the heat load within a repository for the used fuel wastes from LWRs.

- Liquid metal–cooled reactors and other reactors with more-advanced cooling. One such design is the Power Reactor Innovative Small Module (PRISM), a compact modular pool-type reactor developed by GE-Hitachi with passive cooling for decay heat removal.
- Traveling wave reactors that convert fertile material into fissile fuel as they operate, using the process of nuclear transmutation being developed by TerraPower. This type of reactor is also based on a liquid metal primary cooling system. It is also being designed with passive safety features for decay heat removal, and has as a major design goal minimization of life cycle fuel costs by both substantially increasing the burnup percentage and internally breeding depleted uranium.
- Hyperion Power Module (25 MW module). According to Hyperion, uranium nitride fuel would be beneficial to the physical characteristics and neutronics of the standard ceramic uranium oxide fuel in LWRs.[25]

Gen IV reactors are two-to-four decades away, although some designs could be available within a decade. As in the case of Gen III and Gen III+ designs in the United States, Gen IV designs must be certified by the NRC pursuant to 10 CFR Part 52, based on updated regulations and regulatory guides.

The U.S. Department of Energy (DOE) Office of Nuclear Energy has taken responsibility for developing the science required for five Gen IV technologies (Table 3 summarizes their characteristics and operating parameters and also provides information on two versions of the molten salt reactor, which the United States is not currently researching). Funding levels for each of the technology concepts reflects the DOE's assessment of the concept's technological development stage and its potential to meet national energy goals. The Next Generation Nuclear Plant (NGNP) project is developing one example of a Gen IV reactor system, the Very High Temperature Reactor, which is configured to provide high-temperature heat (up to 950°C) for a variety of co-products, including hydrogen production. The NRC is working with DOE on a licensing approach. The earliest potential date for a COL application is the middle of this decade.

In general, Gen IV systems include full actinide recycling and on-site fuel-cycle facilities based on advanced aqueous, pyrometallurgical, or other dry-processing options.[26] Fast reactor research has been active in the United

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[25] Uranium nitride has beneficial traits such as higher thermal conductivity, which results in less retained heat energy. These characteristics make it preferable to oxide fuels when used at temperature regimes greater than the 250–300°C temperatures that characterize LWRs. By operating at higher temperatures, steam plants can operate at a higher thermal efficiency.

[26] The exceptions are Gen IV designs that focus on intrinsically higher burnup and possible breeding of fertile fuel (such as depleted uranium), and thus potentially no refueling of the reactor core—with the consequence that no recycling or reprocessing would be contemplated. The TerraPower Traveling Wave Reactor (TWR) concept is an example of such a Gen IV design.

States and more active in China, France, India, and the countries of the former Soviet Union.[27]

One rationale for closing the fuel cycle with fast reactors is the potentially limited supply of uranium. However, given the current significant economic supplies of uranium, from both primary and secondary stores, the objective of breeding civil plutonium cannot be currently based on commercial needs. This leaves the depletion of the fertile and fissile content of used fuel, including plutonium, the remaining fissile uranium, and the minor actinides, as the remaining key rationale for closing the fuel cycle. Of course, in the final analysis, the ultimate metric for success will be the economics of what is being proposed, all within the constraints imposed by meeting all of the safety, security, and nonproliferation concerns—concerns that are likely to be reinforced by the recent events at Fukushima, Japan.

[27] Small fast reactor facilities (BR-1, BR-2, and BR-5) were constructed in the 1950s and 1960s in the former Soviet Union, and operational results were used to refine the design and construction of larger plants. The large power plant facilities currently developed in this program are the BOR-60, BN-350, BN-600, and BN-800. Japan has built one demonstration FBR, Monju, adding to the research base developed by its older research FBR, the Joyo reactor. Monju is a sodium-cooled, MOX-fueled loop-type reactor with three primary coolant loops, producing 280 MW. Monju began construction in 1985 and was completed in 1991, achieving criticality on April 5, 1994; it was closed in December 1995 after a sodium leak and fire in a secondary cooling circuit. The reactor was restarted in June 2010 (about two years after its expected restart date of 2008). France's first fast reactor, Rapsodie, first achieved criticality in 1967. Rapsodie was a loop-type reactor with a thermal output of 40 MW and no electrical generation facilities; it closed in 1983. France's second fast reactor was the 233 MW Phénix, grid connected since 1973 and still operating as both a power reactor and, more important, as the center of work on reprocessing nuclear waste by transmutation. Superphénix, 1,200 MWe, entered service in 1984 and as of 2006 remains the largest FBR built; it was shut down in 1997 because of a political commitment the left-wing government of the time had made to competitive market forces. At the time of the shutdown, the power plant had not produced electricity for most of the preceding decade. The fast reactor EBR-I (Experimental Breeder Reactor-1) in Idaho became operational on December 20, 1951, when it produced enough electricity to power four light bulbs. The next day it produced enough power to run the entire EBR-I building. This was a milestone in the development of nuclear power reactors in the United States. The next generation of EBR was the Experimental Breeder Reactor-2, which went into service at the Idaho National Engineering and Environmental Laboratory in 1964 and operated until 1994. The EBR-2 was designed to be an "integral" nuclear plant, equipped to handle fuel recycling onsite. It typically operated at 20 MW out of its 62.5 MW maximum design power and provided the bulk of heat and electricity to the surrounding facilities. The world's first commercial Liquid Metal Fast Breeder Reactor, and the only one built in the United States, was the 94 MW Unit 1 at Enrico Fermi Nuclear Generating Station. The plant went into operation in 1963 but shut down on October 5, 1966, because of high temperatures caused by a loose piece of zirconium that was blocking the molten sodium coolant nozzles. After restarting, it ran until August 1972 when its operating license renewal was denied. India's first 40 MW Fast Breeder Test Reactor (FBTR) attained criticality on October 18, 1985. India was the sixth nation to demonstrate the technology to build and operate an FBTR (after the United States, United Kingdom, France, Japan, and the former USSR). India has developed the technology to produce plutonium-rich U-Pu mixed carbide fuel. The Chinese Experimental Fast Reactor (CEFR) was designed in 2003 and built near Beijing by Russia's OKBM Afrikantov in collaboration with OKB Gidropress, NIKIET, and the Kurchatov Institute. The reactor achieved criticality in July 2010, can generate 20 MWe, and will be grid connected in 2011.

Table 3. Characteristics and Operating Parameters of the Eight Generation IV Reactor Systems under Development

	Neutron Spectrum (fast/ thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel Cycle	Size(s) (MWe)	Uses
Gas-cooled fast reactors	Fast	Helium	850	High	U-238[†]	Closed, on site	1,200	Electricity & Hydrogen[‡]
Lead-cooled fast reactors	Fast	Lead or lead-bismuth	480–800	Low	U-238[†]	Closed, regional	20–180** 300–1,200 600–1,000	Electricity & Hydrogen[‡]
Molten salt fast reactors	Fast	Fluoride salts	700–800	Low	UF in salt	Closed	1,000	Electricity & Hydrogen[‡]
Molten salt reactor—Advanced high temperature reactors	Thermal	Fluoride salts	750–1,000		UO_2 particles in prism	Open	1,000–1,500 30–150	Hydrogen[‡]
Sodium-cooled fast reactors	Fast	Sodium	550	Low	U-238 & MOX	Closed	300–1,500 1,000–2,000 300–700	Electricity
Traveling wave reactors	Fast	Sodium	~510	Low	U-238 metal with U-235 igniter seed	Open	400–1,500	Electricity
Supercritical water-cooled reactors	Thermal or fast	Water	510–625	Very high	UO_2	Open (thermal) closed (fast)	1,000–1,500	Electricity
Very high temperature gas reactors	Thermal	Helium	900–1,000	High	UO_2 prism or pebbles	Open	250–300	Electricity & Hydrogen[‡]

* High = 7–15 megapascals

† = With some U-235 or Pu-239

** ‘Battery’ model with long cassette core life (15–20 years) or replaceable reactor module

‡ Such plants can efficiently produce hydrogen because of their high operating temperature characteristic, a characteristic that is also useful for providing process heat to, for example, refineries that would also utilize the hydrogen as a feedstock to upgrade the energy characteristics of the processed fossil fuels.

Used with permission from the World Nuclear Association, “Generation IV Reactors” (World Nuclear Association, June 2010), http://www.world-nuclear.org/info/inf77.html.

THE FUTURE

Public Acceptance and Concerns about Nuclear Waste

Public attitudes will be crucial in determining whether nuclear technologies are part of the portfolio of energy technologies on which the world relies to confront the challenges of the twenty-first century. Two persistent questions are “What is safe enough?” and “What are we going to do about the waste?” Switching from active to passive safety features is a key component of addressing the safety question. Long-term dry cask storage addresses the second question. However, in the very long-term, we will need to develop and implement an acceptable strategy for the disposal of high-level waste and used nuclear fuel. Thus, for the next few decades, the long-term waste issue will remain a nettlesome problem for nuclear energy.

The Investment Barrier

In a highly stressed credit market, the price tag for nuclear construction—at least in the Western world—is too high. The latest overnight cost estimates for a dual-unit nuclear plant with an aggregate capacity of 2,236 MW is $5700 per kilowatt,[28] a doubling in estimated overnight costs over the last 3-4 years. The investment community has shown an increasing interest in SMR designs because of these escalating costs and related financial challenges.

ANL, as part of its update of the 2004 economic study *The Economic Future of Nuclear Power,* is conducting an extensive analysis of the life-cycle costs of both large reactors and SMRs. The revised study will also offer detailed insights into the recent cost increases. The study team is consulting with nuclear vendors (including B&W, NuScale, and Westinghouse) to ensure that the nuclear utility industry plays an integral part in the analysis.

The updated study will focus on key parameters and policy options and will address issues President Obama identified in a recent address on U.S. energy policy.[29]

The study team will use cost estimates for factory-produced modular units and compare this methodology to construction practices used in building larger units. A detailed sensitivity analysis will be performed on the key design and manufacturing parameters. This task requires collaboration with vendors to obtain data on

a. modularization practices;
b. factory designs and manufacturing;
c. factory assembly versus field assembly; and
d. learning-by-doing in both manufacturing and construction.

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[28] Energy Information Administration, *Updated Capital Cost Estimates for Electricity Generation Plants* (Washington, DC: U.S. Department of Energy, 2010), http://www.eia.doe.gov/oiaf/beck_plantcosts/.

[29] "To meet our growing energy needs and prevent the worst consequences of climate change, we'll need to increase our supply of nuclear power. It's that simple. This one plant, for example, will cut carbon pollution by 16 million tons each year when compared to a similar coal plant. That's like taking 3.5 million cars off the road.... On the other side, there are those who have long advocated for nuclear power—including many Republicans—who have to recognize that we're not going to achieve a big boost in nuclear capacity unless we also create a system of incentives to make clean energy profitable. That's not just my personal conclusion; it's the conclusion of many in the energy industry itself, including CEOs of the nation's largest utility companies." Barack Obama, "Remarks by the President on Energy in Lanham, Maryland, IBEW [International Brotherhood of Electrical Workers] Local 26, Lanham, Maryland," February 16, 2010, http://www.whitehouse.gov/the-press-office/remarks-president-energy-lanham-maryland.

Nuclear Energy Demand in Asia

In Asia, 115 nuclear power reactors are in operation, 39 are under construction, and firm plans exist to build an additional 87. If an additional 185 proposed reactors are eventually deployed, this would represent an aggregate electrical capacity of more than 400 GWe in the region. In 2010 alone, this region has exhibited four out of the five units connected to the grid and seven out of the ten where construction has been initiated. Much of the expansion of nuclear power in this region is driven by concerns about energy security, and thus the financing concerns that dominate in the Western world are not as prominent and determinative here.

The Emerging Roles of China, Russia, the Republic of Korea, and India

The future economics of nuclear energy will be determined, in part, by the tooling up and supply chain improvements currently underway in Russia and several non-Western states. Russian and Chinese suppliers will soon meet the needs of their domestic markets and are beginning to ramp up in the expectation of large-scale exports. Korean industry provides components internationally and by 2013 will possess the capacity to forge even the largest nuclear plant components.[30] The Republic of Korea's new very heavy forging capacity will join that of Japan (JSW), China (China First Heavy Industries), and Russia (OMX Izhora). Japan and Korea are already building further capacity (JSW and Doosan, respectively), as is France (Le Creusot), and new capacity is planned in both the United Kingdom (Sheffield Forgemasters) and India (Larsen & Toubro).

GE Hitachi Nuclear Energy (GEH) recently announced it has signed a nuclear power plant development agreement with India's top engineering and construction company, Larsen & Toubro Ltd. The agreement with L&T is an important part of GEH's strategy to establish an extensive network of local suppliers to help build a future GEH-designed Advanced Boiling Water Reactor (ABWR) power station in India. The power station is one of several being planned by India to increase the country's nuclear generation capacity more than tenfold over the next two decades—from 4.1 GW today to 60 GW by 2030. The nuclear power initiative is a key part of India's broader plan to expand its energy infrastructure to meet the country's surging demands for electricity.

Government Support and Partnerships

The U.S. nuclear industry (specifically GE) has expressed frustration that U.S. private industry nuclear developers must compete against government-supported foreign enterprises. Nuclear power in China, Russia, the Republic of Korea, Canada, and France is essentially a government-supported enterprise.

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[30] Doosan Heavy Industries is investing in casting and forging capacity to supply reactor pressure vessels and steam generators for AP-1000 reactors in China and the United States.

For example:

- The French government owns 91 percent of AREVA[31] and 85 percent of EDF.
- The Republic of Korea owns essentially all the technology for the KSNP design (OPR-1000). Two units (Shin Kori Units 3 and 4) are being constructed by Korea Hydro and Nuclear Power Co. (KHNP) using the APR-1400 design model, which has a capacity 1.4 times higher than the OPR-1000. These plants are owned and operated by KEPCO, a company representing a number of independently operating power generating subsidiaries.[32]
- China National Nuclear Corporation (CNNC) is designing the CPR-1000 reactor, and the State Nuclear Power Technology Corporation (SNPTC) is designing the AP-1000 and AP-1400.[33] SNPTC recently announced that ten state-owned enterprises have qualified to supply equipment.
- In Japan, the government encourages companies to establish conglomerates. Toshiba and Hitachi have partnered to build four ABWRs in Japan. However, Japan's main focus is on exports. The Japan Bank of International Cooperation provides partial funding for building Toshiba reactors outside of Japan, and Nippon Export and Investment Insurance provides credit for the export of nuclear power plant components.
- AECL, owned by the Canadian government, is funding the ACR, with small contributions by industry partners.
- Russia is a serious player financing its own technology in India, Thailand, Turkey, and Vietnam.

The Coal Repower, "Thread the Needle" Issue

The paradigm for GEN III+ plants is evolving. If they can be designed, manufactured, and operated economically to replace aging coal plants, the opportunities for nuclear energy to mitigate climate change will be enhanced. The ANL study will analyze this possibility.

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31. This assumes that the Siemens's 30 percent stake is sold to the French government. According to Bloomberg (December 2010), AREVA will raise €900 million ($1.2 billion) in a share sale, bringing in a Kuwaiti sovereign wealth fund alongside the French state to help finance investments.

32. KFPCO owns 51 percent, and public shareholders own a minority stake. In December 2009, KFPCO, supported by Doosan Industries, Hyundai, KOPEC, Samsung, and Westinghouse, as subcontractor, won a contract to build four reactors in the United Arab Emirates. This is just one example of significant infrastructure projects in the Middle East, including desalination plants at Burj Khalifa.

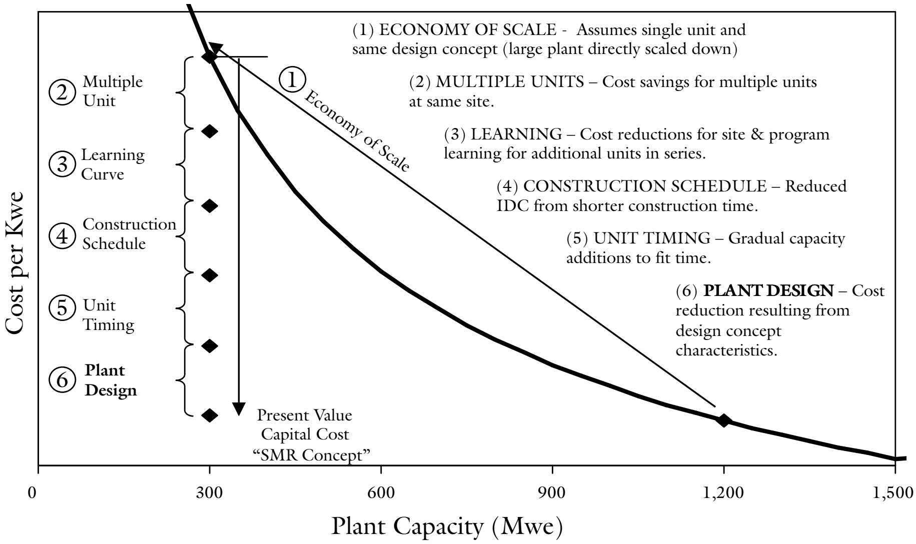
33. The Chinese central and provincial governments are funding all CNNC and SNPTC reactors.

Remaining Barriers

The electric grid infrastructure in many parts of the world is unable to support the deployment of large nuclear power plants. Deployed systems must be appropriate to the scale of the national electric grid and other institutional capabilities. For example, building gigawatt-scale nuclear plants assumes the presence of an appropriately scaled electric grid infrastructure. If this infrastructure is not present, and it is not in many developing countries, then different technologies are needed, namely, grid-appropriate (modular) nuclear reactors. However, the economics of SMRs must be carefully considered. The ANL study will analyze the economic opportunities of deploying SMR technology.

Today, large plants operating in the United States set a high standard for safety, availability, and cost competitiveness. To enter this marketplace successfully, SMR and Gen IV designs must offer a compelling promise of even higher performance or serve a new mission such as waste disposition. In overseas markets, considerations other than economics—for example, energy security—may be determinative, but the economics of nuclear power vis-à-vis its alternatives will also play an important role. Additional development and demonstration is required to bring overnight costs for SMRs to a point that is comparable to commercial-size Gen III units (Figure 3). Finally, the nonproliferation and safety benefits of SMRs will remain unclear until more SMR specifications are known.

Figure 3. Costs of SMRs



For SMRs to be economically feasible, their overnight cost must be comparable (on a cost per kWe basis) to the overnight cost of large nuclear plants. Provided by and reprinted with permission of Westinghouse Electric Corporation.

CONCLUSION

To quote Charles Dickens, "It was the best of times, it was the worst of times…."[34] Nuclear technology has progressed in the past 60 or so years. The growth of nuclear power in Asian countries and the proliferation of Asian suppliers of nuclear power technology have been immense. However, safety, fuel-cycle, nonproliferation, and economic hurdles remain and may become more burdensome, particularly if out-of-the-box innovations to the current state of the art in reactor technology do not reach the marketplace within the next two decades. In the opinion of the authors, passive safety features should be the new standard for all reactor designs going forward. However, the determining factor in establishing future nuclear energy parameters will likely be who wants to invest and where.

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[34] "It was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to heaven, we were all going direct the other way—in short, the period was so far like the present period, that some of its noisiest authorities insisted on its being received, for good or for evil."

List of Acronyms

ABWR	Advanced Boiling Water Reactor
ACR	Advanced CANDU Reactor
AECL	Atomic Energy of Canada Ltd.
AFPR	Atoms for Peace Reactor
AES	АЭС, Russian, Atomic Power Station
ANL	Argonne National Laboratory
ANTARES	AREVA – New Technology based on Advanced gas-cooled REactorS
APR	Advanced Power Reactor
APWR	Advanced Pressurized Water Reactor
ARC	Advanced Reactor Concepts, LLC
B&W	Babcock & Wilcox
BWR	boiling water reactor
CANDU	CANada Deuterium Uranium Reactor
CNNC	China National Nuclear Corporation
CNP	China's Nuclear Power Reactor Series
COL	combined construction and operating license
CPR	Chinese Pressurized Water Reactor
DOE	U.S. Department of Energy
EBR-I	Experimental Breeder Reactor-1
EDF	Électricité de France
ENHS	Encapsulated Nuclear Heat-Source Reactor
EPR	European Pressurized Reactor
ESBWR	Economic Simplified Boiling Water Reactor
FBR	fast breeder reactor
FBTR	Fast Breeder Test Reactor
GA	General Atomics
GE	General Electric
GEH	GE Hitachi Nuclear Energy
GEN I	generation I reactor
GEN II	generation II reactor
GEN III	generation III reactor
GEN III+	generation III+ reactor
GEN IV	generation IV reactor
GWe	gigawatt electric
HPM	Hyperion Power Module
IAEA	International Atomic Energy Agency
IRIS	International Reactor Innovative and Secure

JSW	Japan Steel Works
KNGR	Korean Next Generation Reactor
KSNP	Korean Standard Nuclear Power Plant
kWe	one thousand watts of electric
kWh	kilowatt hour
LANL	Los Alamos National Laboratory
LFR	lead-cooled fast reactor
LLNL	Lawrence Livermore National Laboratory
LWR	light water reactor
MHI	Mitsubishi Heavy Industries
MHR	Modular Helium Reactor
MOX	mixed oxide
MPa	megapascal
MW	megawatt
MWe	megawatts electric
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
OPR	Optimized Power Reactor
ORNL	Oak Ridge National Laboratory
PB-AHTR	Pebble Bed Advanced High Temperature Reactor
PBMR	Pebble Bed Modular Reactor
PNNL	Pacific Northwest National Laboratory
PRISM	Power Reactor Innovative Small Module
PWR	pressurized water reactor
SmAHTR	Small Modular Advanced High Temperature Reactor
SMR	small modular reactor
SNPTC	State Nuclear Power Technology Corporation (China)
SSTAR; SSTAR-H_2 and SSTAR-LM	Small, Sealed, Transportable, Autonomous Reactor of many coolants—two potential coolants are hydrogen and liquid metal
TWR	Traveling Wave Reactor
UO_2	uranium dioxide
VVER	Vodo-Vodyanoi Energetichesky Reactor

Contributors

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Robert Rosner is the William E. Wrather Distinguished Service Professor in the Departments of Astronomy and Astrophysics and Physics at the University of Chicago. He is former President of UChicago Argonne, LLC and former Director of Argonne National Laboratory. Previously he served as Chief Scientist and Associate Laboratory Director of the Center for Physical, Biological, and Computational Sciences at Argonne, Chairman of Astronomy and Astrophysics at the University of Chicago, and Director of the Center for Astrophysical Thermonuclear Flashes at the University of Chicago. He was Rothschild Visiting Professor at the Newton Institute for Mathematical Sciences at the University of Cambridge in 2004. His research is in the areas of plasma astrophysics and astrophysical fluid dynamics and magnetohydrodynamics (including, especially, solar and stellar magnetic fields); high energy density physics; boundary mixing instabilities; combustion modeling; applications of stochastic differential equations and optimization problems; and inverse methods. He is a Fellow of the American Physical Society and a Foreign Member of the Norwegian Academy of Science and Letters. He was elected a Fellow of the American Academy of Arts and Sciences in 2001 and serves as Senior Advisor to the Academy's Global Nuclear Future Initiative. He also serves as a member of the Academy's Council.

The Global Nuclear Future Initiative of the American Academy of Arts and Sciences

There is growing interest worldwide in civilian nuclear power based on the recognition of its potential for meeting increased energy demands. But the spread of nuclear technology, in the absence of rigorous safety regimes, presents unique security risks, including the potential proliferation of weapons capabilities to new states, sub-national, and terrorist groups.

The American Academy's Global Nuclear Future Initiative is working to prevent this dangerous outcome by bringing together constituencies that historically have not communicated effectively—from government policy-makers to heads of nongovernmental organizations, from nuclear engineers to industry leaders, from social scientists to nonproliferation experts—to establish an interdisciplinary and international network of experts working together to devise and implement nuclear policy for the twenty-first century. Our overriding goal is to identify and promote measures that will limit the security and proliferation risks raised by the apparent growing global appetite for nuclear energy.

To help reduce the risks that could result from the global expansion of nuclear energy, the Initiative addresses a number of key policy areas, including the international dimension of the nonproliferation regime, the entirety of the fuel cycle, the physical protection of nuclear facilities and materials, and the interaction of the nuclear industry with the nonproliferation community. Each of these areas has specific challenges and opportunities, but informed and thoughtful policies for all of them are required for a comprehensive solution. We also recognize that "game changers," including natural disasters, terrorism, or other developments, could have a tremendous impact. These events could influence the safety and security of nuclear energy and are being identified and included in our deliberations.

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The Academy was founded during the American Revolution by John Adams, James Bowdoin, John Hancock, and other leaders who contributed prominently to the establishment of the new nation, its government, and its Constitution. Its purpose was to provide a forum for a select group of scholars, members of the learned professions, and government and business leaders to work together on behalf of the democratic interests of the republic. In the words of the Academy's Charter, enacted in 1780, the "end and design of the institution is . . . to cultivate every art and science which may tend to advance the interest, honour, dignity, and happiness of a free, independent, and virtuous people." Today the Academy is both an honorary learned society and an independent policy research center that conducts multidisciplinary studies of complex and emerging problems. Current Academy research focuses on science and technology policy; global security; social policy and American institutions; the humanities and culture; and education. The Academy supports early-career scholars through its Visiting Scholars Program and Hellman Fellowships in Science and Technology Policy, providing year-long residencies at its Cambridge, Massachusetts, headquarters. The Academy's work is advanced by its 4,600 elected members, who are leaders in the academic disciplines, the arts, business, and public affairs from around the world.

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