The Future of the Nuclear Industry Reconsidered

Risks, Uncertainties, and Continued Potential

Ioannis N. Kessides

The World Bank
Development Research Group
Environment and Energy Team
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Abstract

Skeptics point out, with some justification, that the nuclear industry's prospects were dimmed by escalating costs long before Fukushima. If history is any guide, one direct consequence of the calamity in Japan will be more stringent safety requirements and regulatory delays that will inevitably increase the costs of nuclear power and further undermine its economic viability. For nuclear power to play a major role in meeting the future global energy needs and mitigating the threat of climate change, the hazards of another Fukushima and the construction delays and costs escalation that have plagued the industry will have to be substantially reduced. One promising direction for nuclear development might be to downsize

reactors from the gigawatt scale to less-complex smaller units that are more affordable. Small modular reactors (SMRs) are scalable nuclear power plant designs that promise to reduce investment risks through incremental capacity expansion; become more standardized and reduce costs through accelerated learning effects; and address concerns about catastrophic events, since they contain substantially smaller radioactive inventory. Given their lower capital requirements and small size, which makes them suitable for small electric grids, SMRs can more effectively address the energy needs of small developing countries.

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The Future of the Nuclear Industry Reconsidered: Risks, Uncertainties, and Continued Potential

Ioannis N. Kessides

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Introduction

During the last decade, rising concerns about the price and security of fossil fuel supplies and global climate disruption, as well as the large absolute increase in electricity demand throughout the industrialized and developing world, contributed to a resurgence of interest in nuclear power. By the late 2000s, nuclear power was under serious consideration in over 45 countries which did not currently have it (WNA, 2011a).¹ Consideration for building new nuclear capacity was no longer off the table in developed countries like the United States, United Kingdom, and Australia. In fast growing developing economies like China and India, nuclear power became a central component of national energy policy. A "nuclear renaissance"--as it was termed in the press--seemed underway. As of June 2010, 61 units were under construction and around 500 additional reactors were under contract or in the planning stage (figure 1; Arthur D Little, 2010).

Source: Arthur D Little (2010).

An extremely strong record of global nuclear operations (including the absence of any high-profile incidents) over the past two decades led to shifts in perceptions about the

¹ In Europe: Albania, Serbia, Croatia, Portugal, Norway, Poland, Belarus, Estonia, Latvia, Ireland, Turkey. In West, Central and Southern Africa: Nigeria, Ghana, Senegal, Kenya, Uganda, Namibia. In the Middle East and North Africa: Iran, Gulf states including UAE, Saudi Arabia, Qatar & Kuwait, Yemen, Israel, Syria, Jordan, Egypt, Tunisia, Libya, Algeria, Morocco, Sudan. In South America: Chile, Ecuador, Venezuela. In Central and Southern Asia: Azerbaijan, Georgia, Kazakhstan, Mongolia, Bangladesh, Sri Lanka. In SE Asia: Indonesia, Philippines, Vietnam, Thailand, Malaysia, Singapore, Australia, New Zealand. In East Asia: North Korea.

environmental and health risks of nuclear energy. This tendency was reinforced by fading memories of the Three Mile Island and Chernobyl accidents. Moreover, dramatic increases in fossil fuel prices prior to the current global economic contraction and the imperative to cut greenhouse gas emissions came to the fore of public concerns and debates, likely contributed to more positive attitudes toward nuclear power . Between 2005 and 2008, the percentage of Europeans favoring nuclear power increased from 37 to 44 percent, while the share of those opposed to it declined from 55 to 45 percent (EU, 2008). Recent international polls sponsored by the nuclear industry showed substantial support for nuclear power. A survey of more than 10,000 people in 20 countries found that more than two-thirds of the respondents believed that their countries should begin using or increase the use of nuclear energy (NEI, 2009). In the United States, those in favor moved from 49 percent in 1983, when the question was first asked, to 74 percent in 2010 (figure 2). Moreover, by 2010, those who “strongly favor” nuclear energy outnumbered those who are “strongly opposed” by more than three to one (NEI, 2010).

Figure 2 Changing public attitudes toward nuclear power in the United States, 1983–2010

Source (NEI, 2010).

The extraordinary events in Fukushima quickly and fundamentally altered the nature of the nuclear debate.² Once again, the future of nuclear power is clouded in uncertainty. These

² The severity of the nuclear event at Fukushima Daiichi has been rated 7 on the International Nuclear and Radiological Event Scale (INES), the highest level and the same as the 1986 Chernobyl nuclear power plant

events served as a reminder that while the probability of a nuclear plant accident is quite low, its consequences can be extremely severe. Like the disasters at TMI and Chernobyl, Fukushima could cause political fallout, at the global level, which might in turn substantially derail a nuclear renaissance.

A public opinion survey sponsored by the industry and carried out across 24 countries in May 2011 found that 62 percent of the respondents opposed nuclear power, and one quarter (26 percent) of those opposed indicated that they had changed their previously held views because of the events in Japan.³ However, the results varied significantly across countries. Opposition in much of Europe and some developing countries seems to be high: 81 percent of those surveyed in Italy are against nuclear power, 79 percent in Germany, 67 percent in France, 60 percent in Belgium, 81 percent in Mexico, 72 percent in Argentina, 69 percent in Brazil, 67 percent in Indonesia, 61 percent in South Korea, 60 percent in South Africa, and 58 percent in China and Saudi Arabia. Majorities in India, Poland, and the United States continue to support nuclear power (Ipsos, 2011), though support seems to be weakened. According to a Gallup poll conducted in summer 2011, 53 percent of Americans supported continued operation of the nuclear energy facilities that are closest to their homes despite the heightened concerns about safety (NEI, 2011a).

Critics argue that the nuclear renaissance met economic reality and began faltering even before Fukushima. They claim that unlike other industries (e.g. aircraft manufacturing) whose unit costs decline with cumulative technology deployment and output, the nuclear industry actually has been characterized by a negative learning curve and a substantial escalation of construction costs (figure 3).⁴ It is pointed out that the history of the nuclear industry is replete with construction delays and cost overruns. The flagship EPR project at Olkiluoto, Finland—the first nuclear plant ordered in Western Europe since the 1986 Chernobyl accident—is being cited as the penultimate example of the industry’s dismal record in meeting its cost projections and on time delivery. The project, once touted as the showpiece of the nuclear renaissance, is four years

accident. In the days immediately after the crisis began at the Fukushima No. 1 nuclear power plant, the government received a report saying 30 million residents in the Tokyo metropolitan area would have to be evacuated in a worst-case scenario (<http://www.washingtonsblog.com/2011/09/tokyo-evacuation-fukushima-radiation.html>).

³ The countries included in the survey were Argentina, Australia, Belgium, Brazil, Canada, China, France, Great Britain, Germany, Hungary, India, Indonesia, Italy, Japan, Mexico, Poland, Russia, Saudi Arabia, South Africa, South Korea, Spain, Sweden, Turkey, and the United States of America.

⁴ It should be pointed out that the econometric evidence on the learning curve of the nuclear industry is mixed. For an insightful overview, see Jamasb and Kohler (2007).

behind schedule and by some estimates 90 percent over budget—its cost approaching \$5,000 per installed kilowatt (Schneider et al, 2011).

Most neutral analysts would agree that the nuclear industry has been facing persistent problems that raised doubts about its much anticipated renaissance long before Fukushima (van der Zwaan et al, 1999; Nuttall, 2011). The industry's future has been clouded by its ever escalating construction costs, the uncertain economics of maintaining the existing nuclear plants, the challenges of radioactive waste disposal, the risks of proliferation and the continued concerns about safety. Moreover, nuclear power lost some of its appeal because of the unanticipated surge in supply of natural gas from shale in the United States and other countries. The events in Japan are likely to cause major regulatory turbulence, thus further clouding the industry's already uncertain economics.

Figure 3 Average and min/max reactor construction costs for US and France versus cumulative capacity

Source: Grubler (2010).

In the longer term, however, increasing concerns about CO₂ emissions may imply stronger prospects for nuclear power than the near-term, post-Fukushima outlook. Coal-fired generation will have to be reduced in order to limit emissions. Hydropower is cost effective in a

number of locations, but utilization of potential new sites is likely to be limited given that these sites are often less accessible and precious for environmental and social reasons. A major expansion of biofuels would require vast land areas for cultivation, in competition with increasing food production and the preservation of natural ecosystems. The cost characteristics of solar photovoltaics, while much improved, are still unfavorable, except in off-grid locations where the costs of alternatives are even higher. There is considerable interest in the promise of Concentrating Solar Power (CSP), but it is not yet commercially mature, with challenges related to cost, location, and constraints on delivery from source to demand. The most promising renewable technology for the near to medium term is seen by many to be wind power, which is already near commercial viability and is achieving high penetration rates in some countries. Where a wide area power grid can even-out local fluctuations in wind availability, problems of intermittency can be handled even for appreciable shares of wind power in total generation. However, while some countries have a substantial wind resource, in others wind resources are less satisfactory and would require substantial complementary investments in transmission and reserve capacity (Kessides, 2010). Storage also remains a technical and economic challenge, though pumped hydro storage is an option in some circumstances.

Wind and solar are intermittent technologies. A large increase in the quantity of intermittent renewable energy has important implications for the costs of balancing electricity supply and demand in real time. It will certainly require substantial investment in reserve generation capacity, thereby adding to the overall cost of supply. Moreover, the most efficient sites for renewable energy facilities, especially wind and large scale solar, are often located far from load centers, in remote areas and off-shore. To take advantage of these opportunities, very significant investments in new long-distance transmission facilities will be required.

Nuclear power can deliver low-carbon electricity in bulk, without intermittency, and it has a very small land take in contrast to renewable technologies. Although capital costs have risen substantially in recent years, some of this has been due to secular increases in costs of various materials that increase the costs of other capital-intensive generation options. Nuclear power retains the potential to be cost-competitive relative to current investment costs for other large-scale low-carbon alternatives. However, even if the safety concerns related to large nuclear plants with substantial radioactive inventories abate, the huge upfront investment requirements of these plants will constitute a major impediment to their deployment—especially

at a time when many governments face serious fiscal constraints and there is large demand for capital for other sorts of infrastructure investment. The experience at Olkiluoto clearly suggests that the new generation of large-scale reactors will be no easier or cheaper to build than the ones of a generation ago, when construction delays and cost overruns—along with the accidents at TMI and Chernobyl—brought to a halt the last nuclear construction boom (Kanter, 2009). Furthermore, such large-scale nuclear reactors would simply be unsuitable for many developing countries with small electric grids.

For nuclear power to play a major role in meeting the future global energy needs and mitigating the threat of climate change, the hazards of another Fukushima and the construction delays and costs escalation of Olkiluoto have to be substantially reduced. The technical complexity, management challenges, and inherent risks of failure posed by the construction of new nuclear plants have been amplified considerably (perhaps non-linearly) as their size increased to the gigawatt scale and beyond. And so have the financing challenges. One potential solution might be to downsize nuclear plants from the gigawatt scale to smaller and less-complex units. New generations of nuclear reactors are now in various stages of planning and development promising enhanced safety, improved economics, and simpler designs. Small modular reactors (SMRs) are scalable nuclear power plant designs that promise to reduce investment risks through incremental capacity expansion, become more standardized and lead to cost reductions through accelerated learning effects, and address concerns about catastrophic events since they contain substantially smaller radioactive inventory.⁵ Thus, SMRs could provide an attractive and affordable nuclear power option for many developing countries with small electricity markets, insufficient grid capacity, and limited financial resources. They may also be particularly suitable for non-electrical applications such as desalination, process heat for industrial uses and district heating, and hydrogen production. Moreover, multi-module power plants with SMRs may allow for more flexible generation profiles.

The Uncertain Economics of Nuclear Power

In a deregulated global electricity marketplace, economics will be a key consideration in future decisions to build new nuclear plants. Indeed, one of the fundamental problems

⁵ According to the classification adopted by IAEA, Small Reactors are reactors with the equivalent electric power less than 300 MWe, Medium Sized Reactors are reactors with the equivalent electric power between 300 and 700 MWe.

underlying the debate on the future of nuclear power relates to the continuing lack of consensus on what will be the costs of new nuclear generating plants (Joskow and Parsons, 2009). These cost uncertainties have been highlighted by the turbulent experience of Finland's Olkiluoto plant.

The costs of nuclear power consist of four major components:

- *Capital or construction costs*—are those incurred during the planning, preparation and construction of a new nuclear power station;
- *Operations and maintenance*—relate to the management and upkeep of a power station (labor, insurance, security, spares, planned maintenance, and corporate overhead costs);
- *Fuel costs*—reflect the cost of fuel for the power station;
- *Back-end costs*—are those related to the decommissioning of the plant at the end of its operating life and the long-term management and disposal of radioactive waste.

Figure 4 Cost profile of nuclear and gas-fired generation

Source: DTI (2007).

Much of the uncertainty surrounding nuclear power's future costs relates to construction cost—the most important component (roughly two-thirds) of total generating costs (figure 4; Nuttall and Taylor, 2009).

Technical Complexity and Construction Cost Escalation

Nuclear plants are by far the most complex energy systems that were ever designed. Experience suggests that failure is one of the most salient features of technological complexity. In the case of nuclear power, the consequences of failure are horrific on a scale and timeline that no other technology can match. Indeed, nuclear power is an unforgiving technology because human lapses and errors can have ecological and social impacts that are catastrophic and irreversible.

Increasing concerns about reliability and safety have led to nuclear plants designs with ever more built-in safety systems and precautionary redundancies. Nuclear plants have a number of independent backup systems designed to operate in the event that normal operation of the plant is disrupted. As nuclear reactors have grown in size, the scale of the problems associated with failures has grown in step. Thus, the potential economies of scale associated the construction of larger reactors have been largely counterbalanced by the costs of the requisite reliability-enhancing strategies and enhanced redundancy. One of the main consequences of technical complexity and tight-coupling on the one hand, and safety-enhancing strategies, on the other, has been an increase of construction times and a concomitant escalation of the costs of nuclear build over time.⁶ Moreover, the complexity of nuclear reactors and the site-specific character of their deployment have inhibited standardization. The evidence from international nuclear plant construction suggests that standardization plays an important role in increasing learning effects (UofC, 2004). Thus the “one-of-a-kind” approach to large reactor design, construction, and operation has put further pressure on nuclear plant costs.

Nuclear reactor components

Nuclear plants exhibit some uniquely complex features that arise primarily from the fission process and the requirements to sustain and control it and to contain the radioactive materials that it produces. There are several components that are common to most types of reactors:

- *Fuel component*—usually pellets of uranium oxide (UO₂) arranged in tubes to form fuel rods. The rods are placed into fuel assemblies in the reactor core. In a new reactor with

⁶ A technology is tight-coupled if interacting failures propagate swiftly and in an unobstructed manner throughout the system (Rijpma, 1997).

new fuel, a “starter” neutron source is needed to get the reaction going. This typically consists of beryllium mixed with polonium, radium, or other alpha-emitters in welded, corrosion-resistant encapsulations, designed to yield high levels of neutron output without compromising the integrity of the source.

- *Moderator*—this is a substance, spread throughout the reaction space, that is used to slow down the fast neutrons released from fission and absorb a portion of their kinetic energy so as to maintain them in the thermal energy range and thus sustain a controlled chain reaction and cause more fission. The moderator contains light nuclei that do not absorb neutrons. When it collides with a light nucleus (such as hydrogen or carbon), the neutron scatters and loses a considerable fraction of its energy. After a few such scatterings, its energy gets down to the level where it has a high probability of absorption by ^{235}U . There are several materials that can serve as moderators: normal or heavy water, deuterium, graphite, beryllium, and lithium.
- *Control rods*—these are made with neutron-absorbing material such as cadmium, hafnium, iridium, silver, or boron, that are inserted or withdrawn from the core to control the rate of reaction, or to halt it in case of emergency situations such as sudden mechanical or structural damage. For secondary shutdown systems, additional neutron absorbers, usually fluids, are added to the system. The role of control rods is very important. Nuclear fission releases enormous quantities of energy and heat and thus it needs to be controlled in a predictable manner.
- *Coolant*—a liquid or gas circulating through the core to capture and transfer the enormous quantity of heat that is being generated through the fission reactions (in light water reactors the moderator also functions as coolant). In addition to facilitating the transfer and conversion of heat into electrical energy, the coolant ensures that the working temperature of the core is kept within safe operating limits. In order for the coolant to ensure the safety of the reactor and fulfill its intended purpose, it should: have a minimum neutron absorption cross section; exhibit high resistance to both high temperatures as well as high levels of radiation; be non-corrosive in nature otherwise it might damage and corrode the core; should have a high boiling point, if it is liquid, or have a relatively low melting point, if it is solid; be capable of being pumped easily to facilitate circulation. No single material can uniquely satisfy the above criteria. Thus different types of coolants are used in different types of reactors depending on various

factors and parameters. Some of the most commonly used coolants are light water, heavy water, carbon dioxide, helium, sodium and lead-bismuth.

- *Reactor vessel or pressure vessel*—usually a robust (made of thick plates that are welded together) steel vessel containing the reactor core, moderator, and coolant. Neutrons from the fuel in the reactor irradiate the vessel as the reactor is operated. This can embrittle the steel, or make it less tough, and less capable of withstanding flaws which may be present. Embrittlement usually occurs at the vessel’s “beltline,” that section of the vessel wall closest to the reactor fuel. Pressurized water reactors (PWRs) are more susceptible to embrittlement than are boiling water reactors (BWRs) which generally experience less neutron irradiation. Embrittlement is more of a concern for PWRs also because they can experience pressurized thermal shock (PTS). A PTS can occur when cold water is introduced into the reactor vessel (e.g. under an accident scenario) while the vessel is pressurized. Introduction of cold water in this manner can lead to a rapid cooling of the vessel which in turn can cause large thermal stresses in the steel. These thermal stresses, along with the high internal pressure and an embrittled vessel, could lead to cracking and even failure of the vessel (U.S.NRC, 2011a).
- *Steam generator*—part of the cooling system where the heat from the reactor is used to make steam for the turbine (i.e. a heat exchanger). Steam generators can have heights up to 70 feet, weigh as much as 800 tons, and can contain anywhere from 3,000 to 16,000 tubes, each about three-quarters of an inch in diameter. The coolant (treated water), which, is maintained at high pressure to prevent boiling, is pumped through the nuclear reactor core. Heat transfer takes place between the reactor core and the circulating water. The coolant is, then pumped through the primary tube side of the steam generator by coolant pumps before returning to the reactor core. This is, referred to as the primary loop. Heat from the water flowing through the steam generator is transferred to the feedwater in secondary side of the tubes which eventually gets converted to steam that is delivered to the turbine to make electricity. The steam is subsequently condensed via cooled water from the tertiary loop and returned to the steam generator, to be heated once again. These loops also have an important safety role because they constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant as the primary coolant becomes radioactive from its exposure to the core. For this reason, the integrity of the tubing is essential in minimizing the leakage of water between the two

sides of the plant. There is the potential that, if a tube bursts while a plant is operating, contaminated steam could escape directly to the secondary cooling loop.

- *Containment*—the structure around the reactor vessel designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any malfunction inside. The reactor vessel is enclosed within the primary containment structure, consisting of the drywell and wetwell, which is designed to contain radioactive materials released during a reactor accident. The reactor building (typically a 1 meter thick concrete and steel structure) provides the secondary containment, which is intended to prevent any leaks from the primary containment from escaping to the environment. The air in the reactor building is sent through filters to remove any radiation before being released to the outside (Balat, 2007).

Technological factors influencing construction and operation costs

The complexity and sophistication of nuclear technology have significant implications for the costs of constructing and operating nuclear power plants that go beyond those experienced in other conventional generating sources. These costs are especially affected by the unique components of nuclear plants that are designed to contain the radioactive material produced by the fission process and all the levels of safety equipment that are emplaced to prevent the release of such dangerous material in the event of accident.

The design, construction, and operational challenges of nuclear plants became more severe as the reactors have increased in size and complexity. One particularly challenging aspect of design is anticipating potential failure modes within a single nuclear plant component and guarding against the potential interaction among different components—i.e., ensuring that the operation of safety systems is not impaired by failures in unrelated and less critical areas. The risks of such adverse interactions, and hence the design and construction challenges, increased considerably as nuclear plants have become larger because of the concomitant increase in the number and complexity of plant components. The operation of plants also has become more difficult. Many of the control functions required to operate the reactor, or to shut it down during an accident, are handled automatically. During an accident, however, a combination of unanticipated events can interfere with the proper functioning of these automatic safety systems. Nuclear reactor operators are therefore trained to respond to such low probability but potentially very damaging events. Such human interventions are not too problematic in the case of very

simple, small reactors which can be designed with a great deal of inherent safety and operated with less sophisticated control systems. Large nuclear reactors, on the other hand, contain many complex systems that have the potential to interact in unpredictable ways thus making it extremely difficult for operators to respond correctly.

In addition to being highly complex, nuclear technology is also very exacting. The public's demand for super-super safety can only be satisfied with sophisticated control systems that are constructed, maintained, and operated according to very rigid and specific technical standards. Field engineers frequently have to work with extremely restrictive fabrication tolerances and other specifications that increase the level of requisite skills and labor requirements for nuclear plants. In view of the critical importance of safety, nuclear regulatory agencies have developed detailed procedures for monitoring and verifying quality. Thus, the construction of nuclear plants is subjected a variety of regulatory checks, audits, and signoffs. For these reasons, the construction of a nuclear reactor is much more labor intensive relative to a coal plant.

Regulatory ratcheting, construction delays, and cost overruns

One of the consequences of the growing public concerns about the safety of nuclear power plants has been regulatory ratcheting—regulation, inspection and documentation of safety-related materials, equipment, and installation became tighter and more extensive over time. Regulatory stringency increased especially after the two accidents that have indelibly marked the history of nuclear power: the 1979 accident at the TMI nuclear power plant and the 1986 accident at Chernobyl.⁷ It is likely to further escalate after the tragic events at the Fukushima nuclear plant in March 2011.

Starting in the early 1970s, regulatory ratcheting led to a significant increase in the requirements for safety equipment, construction materials, and labor. Between the early and late 1970s, in large part due to the steady increase in regulatory requirements, the quantity of reinforcing and structural steel needed per unit of installed nuclear plant capacity in the US

⁷ The environmental and health effects of the Chernobyl accident were far more severe than those from Three Mile Island. Those differences confirmed the critical importance of inherent safety features—especially a strong containment building enclosing the reactor's primary system. Although about half of the reactor core melted at Three Mile Island, the released radionuclides mostly deposited on the inside surface of the plant or dissolved in condensing steam. The containment building prevented any significant release of radioactive material. Except for some early Soviet-designed systems, most nuclear power plants currently operating have such containment buildings.

increased by 41 percent, the amount of concrete by 27 percent, the lineal footage of piping by 50 percent, and the length of electrical wire and cable by 36 percent (Spiewak and Cope, 1980; Komanoff, 1981).

In addition to increasing the quantity of material and labor inputs, regulatory ratcheting also led to a considerable lengthening of the time required for constructing new nuclear plants. Strict quality control and rigid inspection procedures were responsible for generating large amounts of quality assurance and compliance paperwork. In the US, the time from project initiation to ground breaking—i.e. the time needed to do the initial engineering design, undertake safety and environmental impact analyses and have them reviewed by the NRC and its Advisory Committee on Reactor Safeguards, hold public hearings and respond to received comments and criticisms, and finally to receive a construction permit—increased from an average of 16 months in 1967 to 32 months in 1972, and 54 months in 1980 (Cohen, 1990).

Frequent revisions of quality and safety regulations and backfit requirements—regulatory turbulence—had an even greater impact on construction times and operation patterns. Regulatory turbulence and unpredictability affected in particular the completion time of plants that were in the construction phase. In some cases, to comply with changing regulatory requirements, major components of nuclear construction projects had to be reworked and equipment, piping and cables that were already placed had to be re-engineered and repositioned. Moreover, the supercharged regulatory environment precluded dynamic engineering adaptation and on-the-spot innovation to solve unanticipated design and construction problems. This is because any design or construction modifications could have been considered as serious rule violations. Instead, even minor changes such as moving a pipe or a valve a few inches to remedy a design miscalculation, had to be submitted to the home office for approval and craft labor was forced to stand around waiting. With elaborate and time-consuming inspections and quality control checks on every component and operation (e.g. requiring tests and documentation for every weld), construction delays became inevitable especially for large nuclear plants that generally included a huge number of specific components. Thus the interaction of a very complex technology and regulatory stringency and ratcheting had profound implications for nuclear new build—it lengthened construction times not only in the U.S. but also globally (table 1).

Table 1 Construction time of nuclear power plants worldwide

Period of reference	Number of Reactors	Average construction time (months)
1965-1970	48	60
1971-1976	112	66
1977-1982	109	80
1983-1988	151	98
1995-2000	28	116
2001-2005	18	82

Source: Clerici (2006).

The increase in the quantity of materials and labor required for nuclear plants and the time required for their construction, led to a pronounced escalation in construction costs. According to figure 5, cost escalation was especially dramatic after the TMI accident. It appears that the much-anticipated reduction in unit costs due to learning-by-doing and increasing scale did not materialize. They were more than offset by the higher costs induced by increasing regulation and the longer construction times associated with large plants. Regulatory ratcheting in particular and the continuous reassessment of safety that led to frequent and costly upgrading of the technical designs of plants under construction played a major role.⁸ Moreover, the technical complexity and site-specific nature of large plants inhibited their standardization and the consequent reduction in units costs from learning by doing (Cooper, 2010). Thus, costs escalated as the industry scaled up the size of new build. Indeed, there is some evidence to suggest that the industry has attempted to put together plants that were too large and complex to be efficiently managed by the constructors (Cantor and Hewlett, 1988).

⁸ The findings from several studies (Mooz, 1979; Paik and Schriver, 1979; Komanoff, 1981; Zimmerman, 1982; Cantor and Hewlett, 1988; MaCabe, 1996; Canterbury, 1996) suggest that increasing regulation in the United States led to a yearly increase of approximately 15 percent in plant costs during the 1970s and 1980s. It should be noted that these percentages probably capture the influence of factors other than regulation (e.g. the tendency of the industry to build larger and more complex plants during a period when the technology was not sufficiently mature (UofC, 2004).

Figure 5 Construction costs for US nuclear plants, 1960-2000

Source: Davis (2011).

Since construction accounts for most of the total generating costs of nuclear power, the pronounced escalation in those costs, especially after TMI, had important implications for the economic future and competitiveness of nuclear power. Economic cost-competitiveness is an indispensable precondition for the successful deployment of any electricity generation technology. After all, utilities, especially profit-maximizing ones, make their various business decisions by comparing the costs of generating electricity from alternative energy sources and by determining how these alternatives fit with their current portfolio of technologies. Reactor orders fell sharply after 1974, less than half of the reactors on order in 1974 were ever completed. By the time the Chernobyl disaster occurred in 1986, the U.S. nuclear industry was already dilapidated (Davis, 2011).

The problem of cost escalation seems to be endemic to the nuclear industry and not limited to the construction experience in the United States. The French nuclear program has often been touted as the most successful nuclear scale-up that achieved economies of standardization that eluded the U.S. industry. However, recent analysis suggests that the French program too has been characterized by a substantial escalation of real-term construction costs (figure 6). And that radical design changes were the primary cause for this cost escalation. Interestingly, the prime motivation for these cost-enhancing design changes does seem to have been improved safety imposed by increased regulatory scrutiny. Instead, these non-safety design changes were driven by the desire for larger scale, higher domestic value-added for the nuclear industry, and more output (Grubler, 2010).

Figure 6 Investment costs of French PWRs (per kW yearly averages) over time

Source: Grubler (2010).

The industry also has a notoriously poor historical record on construction cost estimation, realization and time to build. Indeed, the construction of most nuclear plants around the world has been plagued with substantial cost overruns. In the United States, for example, the final costs of plants that began commercial operations in the late 1970s were in some cases several times greater than their initial cost estimates. For the 75 nuclear power plants that were constructed between 1966 and 1986, the average actual cost of construction exceeded the initial

estimates by over 200 percent (table 2). Although there were no new orders after the TMI accident in 1979, utilities sought to complete more than 40 nuclear power projects already under

Table 2 Projected and Actual Construction Costs for U.S. Nuclear Power Plants

Construction Starts		Average Overnight Costs^a		
Year Initiated	Number of Plants^b	Utilities' Projections (Thousands of dollars per MW)	Actual (Thousands of dollars per MW)	Overrun (Percent)
1966 to 1967	11	612	1,279	109
1968 to 1969	26	741	2,180	194
1970 to 1971	12	829	2,889	248
1972 to 1973	7	1,220	3,882	218
1974 to 1975	14	1,263	4,817	281
1976 to 1977	5	1,630	4,377	169
Overall Average	13	938	2,959	207

Source: CBO (2008).

way. For those plants, construction cost overruns exceeded 250 percent (CBO, 2008; Joskow, 2006a).⁹

Prior research and more recently discussions with more than 30 industry members across the nuclear supply chain, have identified several explanatory factors for the observed uncertainty and miscalculation/escalation of construction costs (Zimmerman, 1982; Cantor and Hewlett 1988; Arthur D Little, 2011):

- incorrect understanding of economies of scale—early cost projections tended to ignore the potential diseconomies of scale due to the increased complexity and greater management requirements of larger nuclear plants;

⁹ The overruns in overnight costs did not include additional financing costs that were attributable to post-accident construction delays.

- start of construction before design completion and design flaws that necessitated costly redesign and caused significant construction delays which at a time of high interest rates substantially increased the cost of build;
- an unwieldy licensing process and increasing regulatory requirements often changing in mid-course, leading to regulatory turbulence and construction delays;
- non-uniform designs which inhibited the exploitation of economies of volume and further compounded the complexity of the licensing process);
- hesitant implementation of remedial measures for emerging problems and identified risks and constraints.

Building a large-scale nuclear plant is one of the most complex technical activities that currently can be undertaken because of the exacting, safety-driven requirements and the lack of flexibility to creatively adapt to emerging construction problems. Therefore, it is not surprising that such cost projections would be wrong. However, the industry's cost forecasting might have also been strategically manipulated to secure the agreement of policy makers, regulators, and utility managers with low initial cost projections who would subsequently be locked-in and largely unable to respond in the face of escalating costs.

Critics of nuclear energy point out that past promises by the nuclear industry for cheap power ("power too cheap to meter") have seldom been kept (Greenpeace, 2007). The nuclear industry is claiming that it has learned from its past mistakes. Joskow (2006b) argues that in recent years, non-fuel operation and maintenance costs have fallen significantly, plant capacity factors have increased dramatically, and safety has improved considerably as well. Moreover, it is argued that improved big-project management techniques and new plant designs hold considerable promise for lower and more predictable construction times and costs. Thus, while the history of nuclear build in the U.S. is replete with cost overruns, we must allow for countervailing factors, such as dynamic adaptation in the U.S. regulatory process and other countries' recent experience with new reactor designs. In 1989, the Nuclear Regulatory Commission adopted a new set of licensing procedures that were designed to reduce construction cost uncertainties. These alternative procedures allow utilities to fulfill more regulatory requirements before beginning construction, thereby reducing costly mid-construction design alterations.

Figure 7 Cost overruns of selected nuclear new build projects (as of June 2010)

Source: Arthur D Little (2010).

The experience of the Tokyo Electric Power Company (TEPCO), in the mid-1990s appears to support the renewed optimism about the industry's learning becoming reflected in new reactor designs. According to the 2003 MIT study, verifiable data indicate that TEPCO constructed two advanced boiling-water reactors at costs and schedules close to manufacturers' estimates. Unfortunately, the more recent experiences with Olkiluoto 3, Flamanville 3, and South Texas 3&4 have once again highlighted the tremendous financial risks facing the nuclear industry and shattered the prospects of a nuclear renaissance driven by a cost-competitive industry (figure 7). It should be noted, however, that while multiple delays and budget overruns have been observed recently in the construction of nuclear power plants with large reactors, the experience with smaller units has been more encouraging—e.g., the deployments of the 220 and 540 MWe Indian pressurized heavy water reactors and the 640MWe Canadian CANDU6 have been on schedule and within budget (Kuznetsov and Barkatulla, 2009).

New Generation of Advanced Nuclear Reactors

Nuclear power is an inherently hazardous and costly technology. By the early 1980s it became clear that, due to heightened concerns about safety and the cost performance problems

plaguing the old generation of reactors, a new conceptual design was called for. The industry responded with improved reactor designs, addressing many of the public health and safety risks that plagued the industry since 1979. These improvements promised to make nuclear reactors less vulnerable to accidents—whether due to equipment malfunctions or human error. Furthermore, the newer advanced reactor technologies are designed to be more fuel efficient and have simpler, standardized designs to expedite licensing, and reduce construction time and capital costs.

The design improvements of the next generation advanced nuclear reactors fall into two broad categories: evolutionary, known as Generation III and III+ reactors; and revolutionary, known as Generation IV reactors.¹⁰ Gen III systems have designs that evolved from Gen II reactors. They place strong emphasis on maintaining proven design features to minimize technological risks and thus incorporate mostly incremental improvements (Crimello, 2004). Examples of Gen III designs include the: Advanced Boiling Water Reactor, Advanced Pressurized Water Reactor, AP-600, Enhanced CANDU 6, and System 80+ (ANNEX A). Gen III+ reactor designs are extensions of Gen III concepts that include advanced passive safety features. These designs include the: Economic Simplified Boiling Water Reactor, AP-1000, European Pressurized Reactor, VVER-1200, APR-1400 (ANNEX B) .

Continuing Uncertainties, Cost Overruns and Safety Concerns

Although Gen III/III+ designs are largely based on existing Gen II technologies, they incorporate several important enhancements that are expected to lead to (WNA, 2011b):

- more expedited licensing, shorter construction times, lower capital costs, and reduced vulnerability to operational upsets—all facilitated by simpler, more rugged and standardized design and modularization;
- higher availability and longer reactor operating life—greater than 60 years;
- significant improvements in fuel technology—higher burn-up and greater use of burnable absorbers;
- greater thermal efficiency;

¹⁰ Generation I reactors were the initial designs built in the 1950-1960s, mostly as demonstration units, and except in the UK, none of them are operational today. Generation II reactors are the commercial designs built between the 1960s and 1990s--the present US and French fleets and most of the reactors in operation elsewhere (WNA, 2011b).

- substantially reduced probability of core meltdown—at least an order of magnitude lower core damage frequency relative to existing conventional plants and far exceeding the U.S.NRC requirements, for example;
- greater resistance to structural damage—e.g. from aircraft impact.

Clearly, the above goals point to improved economics and higher levels of safety than the original design concepts—i.e., Generation I and early Generation II systems. However, some of the advanced reactor designs have already experienced serious problems that are reminiscent of the endemic delays and cost overruns that plagued nuclear build years ago. The Gen III+ EPR design has been facing serious construction delays and cost overruns at Olkiluoto. Another Gen III+ design, the AP1000, is facing cost overruns in the plants being built by Westinghouse in China (Ramachandran, 2010). Similarly, the two ABWR reactors of the Lungmen nuclear project in Taiwan that were expected to come online in July 2009 (Unit 1) and July 2010 (Unit 2) have been delayed because of additional funding requirements. Moreover, despite the industry's claims that the new nuclear reactor designs are significantly safer than the currently operating conventional plants, safety concerns continue to be raised about various Gen III/III+ reactors. These concerns have been amplified by the catastrophic events at Fukushima.

Cost escalation

During the past decade, there has been a significant rise in the projected overnight capital costs of Gen III/III+ power plants. This cost escalation has been driven by the substantial increase in material costs, increased safety requirements, and the increase in the cost of capital for power projects in large part caused by the liberalization of electricity markets (Anadon et al, 2011).

The Olkiluoto 3 construction project has become the prime example of all that can still go wrong in economic terms with large-scale nuclear build. The huge power plant under construction on the muddy terrain of this Finnish island was intended to be the showpiece of the nuclear renaissance--the first Generation III+ reactor to be constructed in the world. The largest reactor ever built (net electric output: 1,600 MWe; reactor thermal output: 4,300 MW), with a modular design that was supposed to reduce construction time and costs. Unfortunately, construction problems and delays emerged right from the start. In August 2005, the first concrete was poured. Just a month later, problems with the strength and porosity of the concrete

emerged, signaling construction delays. By February 2006, work was reported to be at least 6 months behind schedule—due to problems with the concrete and also with qualifying welds in the pressure vessel and delays with the detailed engineering designs. In July 2006, the plant’s owner, the utility Teollisuuden Voima Oyj (TVO), admitted that the project was delayed by a year. And, the Finnish nuclear regulator, Säteilyturvakeskus (STUK), published a report that identified a number of quality problems.

In September 2006, Olkiluoto’s construction issues started to affect Areva’s financial performance—it attributed a €300 million fall in its first-half 2006 operating income to reserves set aside to cover past and anticipated future costs at Olkiluoto. In December 2006, only 16 months after the construction began, Areva announced that the project was 18 months behind schedule. In late 2007, the estimated delay was doubled to 36 months and the cost overrun to €1.5 billion (Thomas and Hall, 2009). After four years of construction and thousands of defects and deficiencies, in mid-2009 the reactor’s €3 billion tag climbed at least 50 percent. In June 2010, TVO announced that based on the latest progress information submitted by Areva, the regular operation of the Olkiluoto plant would commence in 2013. However, in October 2011, TVO announced that the plant’s operation may be further postponed until 2014.¹¹ Moreover, in June 2011, Areva increased its claim for cost-escalation damages to €1.9 billion up from €1 billion two years earlier.¹² Olkiluoto 3 was supposed to be supplied by the Areva-Siemens consortium under a fixed-price turn-key contract. It is rapidly becoming a much-cited case study of the implementation challenges facing large projects involving multiple organizations with different and changing priorities and objectives (Ruuska et al, 2009).

Lingering safety concerns

Advanced reactor designs are supposed to offer higher levels of safety because they: (i) are simpler than the current generation of conventional plants; and (ii) rely less on engineered (active) safety systems like pumps and motors and more on natural (passive) safety features like gravity to provide backup cooling water in the event of a LOCA and natural convection to carry heat away (NEI, 2011). The Gen III/III+ plant designs have benefitted from the lessons from the Three Mile Island and Chernobyl accidents. Moreover, in an increasingly competitive electricity

¹¹ <http://www.tvo.fi/www/page/3439/> and <http://www.tvo.fi/www/page/3697/>.

¹² <http://www.tvo.fi/www/page/3628/>.

Figure 8 Evolution of core damage frequency and large release frequency for existing (Generation I and II) and for future reactor types (Generation III/III+)

Source: OECD (2010).

market, utilities have been demanding higher levels of reactor safety along with greater operating efficiency and reliability. A variety of probabilistic safety assessments (PSAs) confirm the trend towards improved levels of predicted safety performance. The design values of the core damage frequency (CDF) and large release frequency (LRF) for Gen III/III+ systems are substantially lower than those of Gen I/II plants (figure 8). For example, the frequency of a large release of radioactivity from a severe accident in a Gen III/III+ system is estimated to be 1600 times lower than that for conventional Gen I plants (OECD, 2010).

It is generally agreed that the Gen III/III+ systems that incorporate simplified and passive approaches to reactor design fix some of the obvious safety problems that are inherent in today's nuclear plants. And that these new advanced reactor designs far exceed the minimum safety standards set by U.S.NRC and other regulatory authorities around the world. However, skeptics point out that there is still not sufficient operating experience to validate the assumptions of the probabilistic risk assessments underlying Gen III/III+ plants. In fact, some experts have suggested that in view of the events at Fukushima, the CDFs for these reactors need to be reanalyzed because they might underestimate the chances of a nuclear plant accident (Goldberg and Rosner, 2011).

A report commissioned by several anti-nuclear groups, is pointing to a potential hazard with the AP1000's unusual containment structure. In existing plants, the containment consists of a steel liner and a concrete dome, and sometimes the steel liner has rusted through. In the new AP1000 design, the liner and the concrete are separated, to allow air to flow between them. This ensures that the temperature inside the steel structure will be kept down by natural forces. But if the steel rusts through, there would be no backup containment behind it. In the new design, metal baffles bolted to the steel direct the air flow, and those baffles are a spot where moisture from the atmosphere could collect. At coastal plants, salty water could collect, and inland, it would be evaporating water from the cooling towers. And inspection would be difficult. If the dome rusted through and an accident occurred, the plant could deliver a dose of radiation to the public that is 10 times higher than the allowed limit by the U.S.NRC. Instead of drawing fresh air past the dome through a chimney effect, the design would expel radioactive contaminants (Wald, 2010).

Concerns have also been raised about the strength of the steel containment vessel and the concrete shield building and thus about the ability of the containment structure to withstand a rise in pressure from steam and potentially explosive hydrogen in the event of an accident. It has been pointed out that the AP1000 is effectively doubling the power output of the AP600 without a proportionate increase in construction costs. The bulk of these cost savings come from scaling back the size of the containment building. As a result, AP1000's ratio of containment volume to thermal power—a yardstick for a reactor's ability to withstand a rise in pressure—is lower than that of most reactors in operation today. Other safety margins are also lower for the AP1000 relative to AP600. For example, during a LOCA the AP1000 would require two properly functioning accumulators (for the rapid injection of cooling water) while the AP600 depends on only one. Similar safety concerns have been expressed about the ESBWR (Piore, 2011; UCS, 2007). Moreover, in 2009, the UK, French, and Finnish nuclear regulatory agencies issued a joint statement on their respective evaluations of EPR's design. The agencies expressed their concern about the adequacy of EPR's safety systems (those used to maintain control of the plant if it goes outside normal conditions), and their independence from the control systems (those used to operate the plant under normal conditions).¹³

¹³ <http://www.hse.gov.uk/newreactors/joint-regulatory-statement.pdf>

The Next Nuclear Frontier: Generation IV and Small Modular Reactors

Generation IV nuclear energy systems aim at significant advances over current-generation and evolutionary reactors in the areas of safety and reliability, sustainability, and economics.¹⁴ They are to be deployable by 2030 and will be based on innovative, next-generation technologies that promise to offer: substantially higher levels of safety and reliability (very low likelihood and degree of reactor core damage, and reduced need for offsite emergency response); enhanced sustainability (more efficient resource utilization and minimal generation of radioactive waste); improved economic performance (life-cycle cost advantage over other sources of energy); and greater resistance to proliferation (unattractive route for diversion or theft of weapons-usable materials). Thus, through their improved safety, economics, and proliferation resistance, Generation IV systems could facilitate nuclear energy's long-term expansion and ensure its sustained contribution to the future global energy mix and security.

The defining characteristics of small modular reactors are their size and modularity. The modular approach facilitates greater standardization of components and processes relative to large-scale reactors. Smaller reactors could offer significant advantages in terms of overall simplicity, speed of build, passive safety features, proliferation resistance, and reduced financial risk. In the past, there was a belief that such small plants may not be economic because they will not be able to exploit important economies of scale. However, as it was noted above, the much-anticipated reduction in unit costs due increasing scale did not materialize—they were offset by the higher costs induced by the longer construction times associated with large plants. Moreover, SMRs are likely to capture the economies of mass production and standardization that have eluded the large-scale nuclear reactors. In any case, most of the cost estimates for small nuclear reactors have not yet been tested by actual construction and operation. Only time and experience will verify the claims made by vendors and the industry.

Generation IV

Development of Generation IV systems is an international collaborative undertaking. Twelve countries (Argentina, Brazil, Canada, China, France, Japan, Republic of Korea, the

¹⁴ It should be noted that according to Rothwell and Van de Zwaan (2002), today's dominant nuclear power technology (the LWR) is not "intermediate sustainable". Thus, if the nuclear power industry is to be sustainable, it needs to develop new technologies.

Russian Federation, Republic of South Africa, Switzerland, the United Kingdom, United States) and Euratom are participating in the planning, testing and development of these systems under the auspices of the Generation IV International Forum (GIF). After an in-depth analysis of the different available technologies and design options, GIF selected six concepts as the most promising, and decided to target all R&D efforts on these systems (table 3): the very-high-temperature reactor (VHTR); the sodium-cooled fast reactor (SFR); the supercritical-water-cooled reactor (SCWR); the gas-cooled fast reactor (GFR); the lead-cooled fast reactor (LFR); the molten salt reactor (MSR)—see ANNEX C. Four of the Generation IV designs are high-temperature reactors that can generate both electricity and high-quality process heat for a wide range of industrial purposes—petroleum refining, chemical processes, and large-scale hydrogen production (Bouchard, 2009).

Table 3 Generation IV systems

SYSTEM	NEUTRON SPECTRUM	COOLANT	TEMP (°C)	FUEL CYCLE	SIZE (MWe)
VHTR Very High Temperature Gas Reactor	thermal	helium	900-1000	open	200-300
SFR Sodium-cooled Fast Reactor	Fast	sodium	550	closed	30-150 300-1500 1000-2000
SCWR Supercritical Water-cooled Reactor	thermal/ fast	water	510-625	open or closed	300-700 1000-1500
GFR Gas-cooled Fast Reactor	Fast	helium	850	closed	1200
LFR Lead-cooled Fast reactor	Fast	lead	480-800	closed	20-180 300-1200 600-1000
MSR Molten Salt Reactor	Epithermal	fluoride salts	700-800	closed	1,000

Source: Bouchard (2009).

Small Modular Reactors

In recent years, small modular reactors (SMRs)—350 MWe or less, compared to a typical nuclear power plant of 1000 MWe—have been attracting the attention of government officials, regulators and energy leaders around the world. These designs incorporate innovative approaches to achieve simplicity, improved operational performance, and enhanced safety. They offer a number of distinct advantages:

- small size and modular construction—this would allow these reactors to be manufactured completely in a factory and delivered and installed module by module, improving component manufacturing productivity through learning effects while reducing construction time, financing costs, and investment risks;
- substantially simpler designs (fewer systems)—this leads to a lower frequency of accident initiators and events that could cause core damage in comparison to the complex current generation plants;
- a diverse set of useful applications—low-carbon electricity generation in remote locations with little or no access to the grid, industrial process heat, desalination or water purification, and co-generation applications (e.g. in the petrochemical industry);
- an expanded set of potential siting options—their small size makes them suitable for small electric grids or for locations that cannot accommodate large-scale plants;
- capping safety and proliferation hazards—compared to large-scale reactors, SMRs have a larger surface-to-volume ratio (easier decay heat removal), lower core power density (more effective use of passive safety features), smaller core inventory relative to traditional large-scale reactors, and multi-year refueling so that new fuel loading is needed very infrequently.

Small modular reactors have compact designs—e.g. the containment vessels of 25 Westinghouse SMRs (225 MWe each) could fit into a single AP-1000 containment vessel—and could be manufactured in factories or other central facilities and then transported (along with the necessary containment walls, turbines for generating electricity, control systems, and so on) to the site of a future plant by track or rail. Building reactors in a factory could substantially decrease construction times and lead to savings on both construction and financing costs. Thus the small size and modularity of SMRs could make them more affordable to small utilities and

developing countries by decreasing capital costs (i.e. requiring less lumpy capital investments) and construction times (Chu, 2010; Aness, 2011).

In general, due to their significantly smaller size and simpler design, SMRs require smaller operator participation for both normal steady-state operations and responding to transients and postulated accidents. The potential radiological consequences of any accidents are much smaller than those of existing large-scale plants, due to the smaller source terms (the radionuclide inventory is orders of magnitude less). Moreover, the physical layout and reduced size of an SMR plant (the smallest SMRs will occupy less than one acre with perhaps three acres of land needed to support plant activities) also contribute to making management of an emergency simpler (ANS, 2010).

Economies of Scale and the Economics of Smaller Sized Nuclear Reactors

Most of the nuclear reactors currently in operation are medium- to large-scale plants sized at 500-1500 megawatts, utilizing tested technologies. The first generation nuclear power plants had a capacity of about 300-500 megawatts. However, because of the general belief that nuclear power operations are characterized by significant economies of scale at the plant level, there was a definite trend toward larger units.¹⁵ By the mid-1960s, the industry scaled up to about 800 megawatts and, before those units were completed, new ones with capacities of over 1300 megawatts were planned and constructed (Cantor and Hewlett, 1988).

Econometric evidence on economies of scale in nuclear power is scant and fairly mixed. The determination of how scaling-up affects unit costs has been marred by methodological uncertainties (e.g. whether overnight costs as commonly calculated can accurately represent economies of scale), the lack of an internationally agreed upon definition of the basic variables and standards for nuclear power plant costing (different cost assessments make varying assumptions that render direct comparisons among them very difficult), the growing divergence between good and poor nuclear plant construction performance, and the scarcity of new orders (especially in the United States) in recent years. The above difficulties notwithstanding, several studies from around the world have sought to estimate the savings in overnight costs arising from economies of scale when the size of power plants increases from 300 to the 1300 MWe range (UoC, 2004).

¹⁵ In the United States the industry and the regulatory authorities assumed that nuclear unit costs would decline by 20 to 30 percent with the doubling of reactor size (Komanoff, 1981).

As the industry scaled up during the 1970-1990 period, construction time schedules increased significantly. An increase in construction time generally results in time-related costs like interest and inflation. And although it is intuitively less clear, there also exists a relationship between construction time and overnight costs—construction delays could imply additional regulatory burdens (since regulation tends to increase over time), higher labor costs (since workers are often laid off and subsequently re-hired), and greater project coordination, supervision, and morale problems (as the recent experience from the EPR project at Olkiluoto clearly indicates). When construction time effects are taken into account, it appears that, at least in the United States, nuclear plant construction has been characterized by very modest, if any, economies of scale. In fact some studies have even detected diseconomies of scale (Cantor and Hewlett, 1988; UofC, 2004).

Capital costs estimates for SMRs are very preliminary given that these systems are in the early stages of their development and there is lack of data regarding their construction cost. Thus, the requisite data does not yet exist to perform an adequate comparative assessment of SMR competitiveness. Still, it can be plausibly argued that because of economies of scale SMRs will suffer a significant economic disadvantage compared to large reactors in terms of their overnight costs per unit of installed capacity. Specific capital costs (i.e. capital costs per unit of installed capacity) are expected to decrease with size because of fixed set-up costs (e.g. siting activities or earth works for connecting to the transmission grid), more efficient utilization of primary inputs (e.g. raw materials), and the higher performance of larger components (e.g. pumps, heat exchangers, steam generators, etc.). Several studies have employed the following scaling function to illustrate the effect of changing from a plant unit size P_0 to a plant of similar design with capacity P_1 :

$$\text{Cost}(P_1) = \text{Cost}(P_0) \times (P_1/P_0)^n$$

where $\text{Cost}(P_1)$ and $\text{Cost}(P_0)$ are the costs of power plants of size P_1 and P_0 respectively, and n is the scaling factor for the entire plant.¹⁶ Overnight cost estimates from France, Canada, and the United States point to a scaling factor in the range of 0.4 to 0.7, at the plant level (NEA, 2000). These estimates imply that doubling the reactor size leads to a reduction in overnight unit costs roughly between 19 and 34 percent. It should be noted, however, that the above scale effects

¹⁶ This is an overall scaling law for the entire plant. Different components of the plant may have substantially different scaling exponents.

apply only if the reactors that are being compared have very similar designs and employ the same components. SMRs have several components that are scaled-down versions of larger reactor designs. However, SMRs also eliminate the need for many components that are an integral part of the larger reactors. Moreover, they include components that are based on entirely different design concepts. Thus, all of these considerations have to be explicitly taken into account when comparing the capital costs of reactors with different sizes. Otherwise, the inference that smaller reactors have substantially higher capital costs per unit of capacity may be based on a misapplication of the economies of scale principle (Mycoff et al, 2010).

SMRs offer a number of advantages that can potentially offset the overnight cost penalty that they suffer relative to large reactors. Indeed, several characteristics of their proposed designs can serve to overcome some of the key barriers that have inhibited the growth of nuclear power. These characteristics include (Carelli et al, 2010; Kuznetsov, 2010):

- ***Reduced construction duration.*** The smaller size, lower power, and simpler design of SMRs allow for greater modularization, standardization, and factory fabrication of components and modules. Use of factory-fabricated modules simplifies the on-site construction activities and greatly reduces the amount of field work required to assemble the components into an operational plant. As a result, the construction duration of SMRs could be significantly shorter compared to large reactors leading to important economies in the cost of financing.
- ***Investment scalability and flexibility.*** In contrast to conventional large-scale nuclear plants, due to their smaller size and shorter construction lead-times SMRs could be added one at a time in a cluster of modules or in dispersed and remote locations. Thus capacity expansion can be more flexible and adaptive to changing market conditions. The sizing, temporal and spatial flexibility of SMR deployment have important implications for the perceived investment risks (and hence the cost of capital) and financial costs of new nuclear build. Today's gigawatt-plus reactors require substantial up-front investment—in excess of US\$ 4 billion. Given the size of the up-front capital requirements (compared to the total capitalization of most utilities) and length of their construction time, new large-scale nuclear plants could be viewed as “bet the farm” endeavors for most utilities making these investments. SMR total capital investment costs, on the other hand, are an order of magnitude lower—in the hundreds of millions of dollars range as opposed to the

billions of dollars range for larger reactors. These smaller investments can be more easily financed, especially in small countries with limited financial resources.

SMR deployment with just-in-time incremental capacity additions would normally lead to a more favorable expenditure/cash flow profile relative to a single large reactor with the same aggregate capacity—even if we assume that the total time required to emplace the two alternative infrastructures is the same. This is because when several SMRs are built and deployed sequentially, the early reactors will begin operating and generating revenue while the remaining ones are being constructed. In the case of a large reactor comprising one large block of capacity addition, no revenues are generated until all of the investment expenditures are made. Thus the staggered build of SMRs could minimize the negative cash flow of deployment when compared to emplacing a single large reactor of equivalent power (Kuznetsov and Barkatullah, 2009).

- ***Better power plant capacity and grid matching.*** In countries with small and weak grids, the addition of a large power plant (1000 MWe or more) can lead to grid stability problems.¹⁷ The incremental capacity expansion associated with SMR deployment, on the other hand, could help meet increasing power demand while avoiding grid instability problems.
- ***Factory fabrication and mass production economies.*** SMR designs are engineered to be pre-fabricated and mass-produced in factories, rather than built on-site. Factory fabrication of components and modules for shipment and installation in the field with almost Lego-style assembly is generally cheaper than on-site fabrication. Relative to today's gigawatt-plus reactors, SMRs benefit more from factory fabrication economies because they can have a greater proportion of factory made components. In fact, some SMRs could be manufactured and fully assembled at the factory, and then transported to the deployment site. Moreover, SMRs can benefit from the “economies of multiples” that accrue to mass production of components in a factory with supply-chain management.
- ***Learning effects and co-siting economies.*** Building reactors in a series can lead to significant per-unit cost reductions. This is because the fabrication of many SMR

¹⁷ The general “rule of thumb” is that the unit size of a power plant should not exceed 10 percent of the overall electricity system capacity (NEA, 2011).

modules on plant assembly lines facilitates the optimization of manufacturing and assembly processes. Lessons learned from the construction of each module can be passed along in the form of productivity gains or other cost savings (e.g. lower labor requirements, shorter and more efficiently organized assembly lines) in successive units. Moreover, additional learning effects can be realized from the construction of successive units on the same site. Thus multi-module clustering could lead to learning curve acceleration. Since more SMRs are deployed for the same amount of aggregate power as a large reactor, these learning effects can potentially play a much more important role for SMRs than for large reactors (Kuznetsov, 2008a).

- ***Design simplification.*** Many SMRs offer significant design simplifications relative to large-scale reactors utilizing the same technology. This is accomplished through the adoption of certain design features that are specific to smaller reactors. For example, fewer and simpler safety features are needed in SMRs with integral design of the primary circuit (i.e. with an in vessel location of steam generators and no large diameter piping) that effectively eliminates large break LOCA.

Clearly one of the main factors negatively affecting the competitiveness of small reactors is economies of scale—SMRs can have substantially higher specific capital costs as compared to large-scale reactors. However, SMRs offer advantages that can potentially offset this size penalty. As it was noted above, SMRs may enjoy significant economic benefits due to shorter construction duration, accelerated learning effects and co-siting economies, temporal and sizing flexibility of deployment, and design simplification. When these factors are properly taken into account, then the fact that smaller reactors have higher specific capital costs due to economies of scale does not necessarily imply that the effective (per unit) capital costs (or the levelized unit electricity cost) for a combination of such reactors will be higher in comparison to a single large nuclear plant of equivalent capacity (figure 9; Kuznetsov and Barkatullah, 2009; Mycoff et al, 2010).

In a recent study, Mycoff et al (2010) provide a comparative assessment of the capital costs per unit of installed capacity of an SMR-based power station comprising of four 300 MWe units that are built sequentially and a single large reactor of 1200 MWe. They employ a generic mode to quantify the impacts of: (1) economies of scale; (2) multiple units; (3) learning effects; (4) construction schedule; (5) unit timing; and (6) plant design.

Figure 9 Factors affecting the competitiveness of SMRs

Source: Mycoff et al (2010).

To estimate the impact of economies of scale, Mycoff et al assume a scaling factor $n=0.6$ and that the two plants are comparable in design and characteristics—i.e. that the single large reactor is scaled down in its entirety to $\frac{1}{4}$ of its size. According to the standard scaling function, the hypothetical overnight cost (per unit of installed capacity) of the SMR-based power station will be 74 percent higher compared to a single large-scale reactor. Based on various studies in the literature, the authors posit that the combined impact of multiple units and learning effects is a 22 percent reduction in specific capital costs for the SMR-based station. To quantify the impact of construction schedule, the authors assume that the construction times of the large reactor and the SMR units are five and three years respectively. The shorter construction duration results in a 5 percent savings for the SMRs. Temporal flexibility (four sequentially deployed SMRs with the first going into operation at the same time as the large reactor and the rest every 9 months thereafter) and design simplification lead to 5 and 15 percent reductions in specific capital costs respectively for the SMRs. When all these factors are combined, the SMR-based station suffers a specific capital cost disadvantage of only 4 percent as compared to the single large reactor of the same capacity.

Alternative SMR Technologies

SMRs can be classified according to the reactor technology and coolant. A number of concepts and designs of advanced SMRs are being analyzed or developed in several countries: Argentina, Brazil, China, Croatia, India, Indonesia, Italy, Japan, the Republic of Korea, Lithuania, Morocco, Russian Federation, South Africa, Turkey, USA, and Vietnam (Kuznetsov, 2008b). Designs under development include (ANNEX D):

Light Water Reactors

SMR designs based on light water reactor technologies are similar to most of today's large pressurized water reactors and as such they have the lowest technological risk and several are considered to be very close to commercial deployment. Still these designs incorporate innovative technologies and novel components to achieve simplicity, improved operational performance, and enhanced safety. They are typically less than 300 MWe and could be used to replace older fossil-fired power stations of similar size.

High-Temperature Gas-Cooled Reactors

The high-temperature gas-cooled reactors (HTGRs) provide broad flexibility in application and in the utilization of the fuel. One of the key advantages of HTGRs is the high outlet coolant temperatures compared to conventional reactors. Core outlet temperatures can range from around 650°C to 1000°C for very advanced reactors-- these high operating temperatures allow for greater thermal efficiencies. The HTGR can be used with either steam cycle or gas turbine generating equipment, and as a source of high temperature process heat. High reactor outlet temperatures can also drive endothermic reactions to produce hydrogen. Fuel cycle options include: (i) low enrichment, where enriched uranium fuel is burned and Pu is recycled; (ii) Th-233, where enriched uranium and Th is burned and U-233 (and U-235) is recycled; (iii) Pu utilization in Th -U-233, where Pu and Th fuel is burned and Pu and U-233 is recycled (Th-228 is saved in interim storage for decay before refabrication; Shropshire and Herring, 2004).

Liquid Metal and Gas-Cooled Fast Reactors

Fast neutron reactors are smaller and simpler than LWRs, have better fuel performance, and substantially longer refueling intervals. They operate at or near atmospheric pressure (no

pressure vessels) and have passive safety features. Liquid metal or gas-cooled fast reactor technologies might be suitable for distributed energy applications for electricity, district heating and water purification. Fast reactors could also provide sustainable nuclear fuel cycle services, such as breeding new fuel and consuming recycled nuclear waste as fuel. They could also use material from former nuclear weapons and thus reduce proliferation risks.

Capping Safety Hazards

Most SMR concepts envision widespread deployment of a large number of small nuclear plants sited in diverse environments and frequently in close proximity to users. These considerations place very stringent requirements on reliability and safety performance—arguably even more exacting relative to traditional large-scale nuclear plants. The need for enhanced levels of safety has led to design options that maximize the use of inherent and passive safety features and incorporate additional layers of “defense in depth” (IAEA, 2009).¹⁸ These safety features can be more easily and effectively implemented in SMRs because of their larger surface-to-volume ratio, reduced core power density, lower source term, and less frequent (multi-year) refueling. For example, large surface-to-volume ratios facilitate the passive (with no external source of electrical power or stored energy) removal of decay heat.

SMRs employ an enveloping design approach that seeks to eliminate or prevent as many accident initiators and accident consequences as possible. Any remaining plausible accident initiators and consequences are dealt with appropriate combinations of active and passive safety systems. In water-cooled SMRs, the integration of steam generators and pressurizers within the reactor vessel eliminates large-diameter pipes and penetrations in the reactor vessel, thereby reducing substantially the risk of LOCAs. Moreover, in some designs the application of in-vessel control rod drives eliminates the risk of inadvertent control rod ejections that lead to reactivity insertion accidents. Loss of coolant accidents may also be prevented with compact loop designs that employ short piping and fewer connections between components (Kuznetsov, 2009).

¹⁸ An approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures (<http://www.nrc.gov/reading-rm/basic-ref/glossary/defense-in-depth.html>).

In HTGRs, the fuel particles consist of fissionable fuel kernels with tri-structural isotropic (TRISO) coating.¹⁹ The TRISO coating system constitutes a miniature pressure vessel that is capable of containing the radionuclides and gases generated by fission of the nuclear material in the kernel. One of the coating layers consists of silicon carbide (a strong refractory material) which can retain radionuclides at extremely high temperatures under all accident conditions—temperatures can remain at 1600°C for several hundred hours without loss of particle coating integrity. Furthermore, the graphite holding the TRISO-coated particles together can withstand even higher temperatures without structural damage.²⁰ And the massive graphite structures in the core create an extremely large heat capacity. The combination of large thermal margins, low power density of the core, and relatively large length-to-diameter ratio of the core, allow for very slow and stable response to transients caused by initiating events and for passive heat removal (INL, 2011).

The effectiveness of passive safety features can be illustrated by comparing outcomes from probabilistic risk analysis (PRA). In 1991, a Level-2 PRA was developed for the EBR-II fast neutron spectrum experimental breeder reactor—a 21 MWe plant—to compare its operational risk to that of commercial LWR's for which PRA's were available. EBR-II employs an extensive array of passive and inherent safety measures to back up traditional active safety systems. This PRA exercise showed that for EBR-II the risk of simply violating a fuel pin technical specification (with no core damage) is less than the risk of significant core disruption for the LWRs of the time. The point of the PRA comparisons is that application of passive and inherent safety measures as incorporated in SMRs can help to overcome the increase in numbers of SMRs needed to deliver the same societal energy provided by a smaller number of large-sized LWRs. Similarly, preliminary Level-1 PRA results for the NuScale Power Reactor indicate a total single-module mean CDF of 2.8×10^{-8} /reactor-year, well below that of existing nuclear plants. And for the VK-300, the probability of severe core damage has been estimated to be less than 2.0×10^{-8} /reactor-year (Hill et al, 1998; Kuznetsov and Gabaraev, 2007; Modarres, 2010).

¹⁹ Fuel kernels are coated with successive layers. The innermost layer is porous carbon, which allows fission products to collect without creating internal pressure. The next layer is pyrolytic carbon, followed by silicon carbide and a final pyrolytic carbon layer. These outer three layers create a compound barrier against fission product release—the silicon carbide coating plays the dominant role.

²⁰ Thousands of TRISO-coated particles are held together in a carbonaceous material forming a cylindrical fuel compact (prismatic HTGR) or spherical fuel element (pebble bed HTGR).

SMRs have a smaller fuel inventory and thus a reduced source term. So on top of reduced hazard of core damage, the hazard attendant to release of radioactivity is also reduced per deployed SMR. The combination of reduced probability of core damage failure, a reduced source term, and additional fission product release barriers, could offer major advantages for emergency planning and response.

Summary

Throughout its history, nuclear power has been controversial and susceptible to instinctive rejection. The public's often unfavorable attitudes can be attributed to concerns about the potential hazards of reactor meltdowns, unresolved issues related to nuclear waste disposal, and potential risks of diversion and proliferation of fissile material. The Fukushima accident serves as a stark reminder that nuclear power is indeed a complex and unforgiving technology whose malfunctioning can have catastrophic and long-lasting ecological and social consequences. Once again, the public's confidence in nuclear power has been shaken. Not surprisingly, the calamity in Japan has stimulated very rigorous reviews of nuclear policy around the world. Nuclear power is facing a cloudy future.

Skeptics point out, with some justification, that the nuclear industry's prospects were dimmed by skyrocketing costs long before Fukushima. Nuclear construction costs have escalated because of the increasing complexity of large-scale reactors, site-specific and one-of-a-kind nature of deployment (lack of standardization within the licensing, construction and operation of nuclear power plants), and chronic construction delays. Advocates and skeptics seemed to agree that the industry could not afford another Three Mile Island or Chernobyl accident. If history is any guide, one direct consequence of Fukushima will be more stringent safety requirements and regulatory delays that will inevitably increase the costs of nuclear power and further undermine its economic viability.

Like all past nuclear crises, Fukushima will raise the stakes for advocates, foes, and regulators alike. In most countries, public opinion is shifting in a more critical direction against nuclear power. And yet it would be decidedly premature to conclude, as some critics have done, that this is the end of nuclear power. The energy environment for the 21st century remains opaque and uncertain—especially in developing countries. Because of the shortage of low-cost substitutes for high carbon-emitting technologies, given current technological capabilities of

low-carbon alternatives, supplying the world's energy needs while stabilizing greenhouse gas emissions to prevent dangerous climate disruption is likely to prove a far greater challenge than more optimistic supporters of green energy seem to consider. One must also bear in mind that while current low-carbon technologies are bound to improve in the future as a result of both R&D and commercial investment, that improvement is not automatic, and nuclear technology could be expected to improve as well.

To meet the challenge of supplying the world's energy needs while stabilizing greenhouse gas emissions in a cost-effective way that is not overly disruptive to economic growth, contributions from a combination of existing, improved or transitional, and advanced technologies on both the supply and demand side of the energy system will be required. Advances are needed in order to effectively: (i) increase efficiency in energy use; (ii) expand the deployment of renewable technologies; (iii) effect carbon capture and storage; and (iv) expand nuclear power.²¹ Many of the needed technologies confront substantial hurdles and even innate physical limits. The solutions to the twin challenges of energy security and climate change are likely to prove complex, with several important technical (scientific and engineering) and social (economic and political) dimensions to consider.

In the face of significant technological and market risks and uncertainties, prudence calls for technological diversification. At this juncture we are not in a position to take off the table any of the existing options, including nuclear power. At present, nuclear energy is the only carbon-free option that is deployed already on a large scale and has the technical capability to expand to the terawatt level (Van der Zwaan, 2010).

Within this context of the urgent need to develop a full arsenal of low-carbon energy technologies, nuclear power is still viewed by many with a great deal of skepticism, and in fact continues to elicit considerable opposition from various electorates. Such opposition has increased considerably after the catastrophic events at Fukushima. For nuclear power to play a major role in the world's future energy mix, the hazards of another Fukushima have to be substantially reduced. However, even if the heightened safety concerns abate, the huge construction delays and cost overruns that have plagued the nuclear industry will constitute a major impediment to its revival—especially at a time when many governments face serious

²¹ For very thoughtful analyses of nuclear power in the context of sustainable development see Nuttall (2008b) and Van der Zwaan (2008).

fiscal constraints. Moreover, today's large-scale nuclear reactors would simply be unsuitable for most developing countries with small electric grids.

One promising direction for nuclear development might be to downsize reactors from the gigawatt scale to less-complex smaller units (with substantially smaller radioactive inventory) that are more affordable. Modular, scalable nuclear reactor designs could: (i) enhance component manufacturing productivity while reducing construction time, financing costs, and investment risks; (ii) cap safety hazards because of their passive or inherent safety features and reduced radioactive inventory; (iii) more effectively address the energy needs of small developing countries because of the lower capital requirements and suitability for small electric grids.

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ANNEX A

Generation III Reactors

There are currently only four Generation III reactors in operation around the world—all of one type and none of them in the United States.

Advanced Boiling Water Reactor (ABWR)

The ABWR, designed by GE Hitachi Nuclear Energy (GEH) and Toshiba, is a single-cycle, force-circulation, boiling-water reactor (BWR), with a rated power of 1350 MWe. It incorporates features of the BWR systems in Europe, Japan, and the United States, and uses improved electronics, computer, turbine, and fuel technology.

ABWR's safety systems are diverse and include several passive accident mitigation features. The following new systems are adopted in ABWRs: (1) a reactor internal pump (RIP) for the reactor coolant recirculation system—the RIP is mounted to the bottom of the reactor pressure vessel and thus no external recirculation piping or jet pump is required; (2) a fine motion control rod drive (CRD) system—the CRD utilizes an electric motor drive for normal operation and a conventional hydraulic drive for emergency insertion (scram), thus ensuring a fully reliable emergency insertion system; (3) a reinforced concrete containment vessel with steel liner for the reactor containment vessel--the use of reinforced concrete provides sufficient strength to withstand the high internal pressure postulated during accidental condition, and the use of a steel liner ensures the required air seal is maintained; (4) three divisions high pressure emergency core cooling systems (ECCSs)-- all three sections of the ECCS have a high pressure injection system, thus ensuring that in the event of a loss of coolant accident, the core flooding will be maintained and safety will be preserved; (5) a high efficiency turbine system—it uses of a 52-inch long blade for the last stage of the turbine, a two-stage moisture separator-reheater, and a heater drain pump-up system connected to the condensate system (U.S.NRC, 2011b; Tsuji et al, 1998).

ABWR remains the world's only Generation III design in operation. There are four ABWR units in operation in Japan, another three units are near completion and commercial operation in Taiwan and Japan, and four more units are planned in Japan. The U.S. Nuclear

Regulatory Commission (NRC) certified the ABWR design in May 1997.²² In August 2006, GE Energy's nuclear business and the STP Nuclear Operating Company signed a project development agreement to study the deployment and begin licensing activities for the construction of two ABWRs in Texas—the first ABWRs to be constructed in the United States. After having spent \$331 million on the project, in April 2011, NRG Energy (STP's 44% owner) officially ended plans to build the two ABWRs (Sauder, 2011).

Advanced Pressurized Water Reactor (APWR)

Designed by Mitsubishi Heavy Industries (MHI), the APWR is a 4-loop pressurized water reactor. Its core size is increased relative to a typical 4-loop plant from 193 to 257 fuel assemblies leading to a 30 percent higher thermal output—thermal power rating of 4451 MWt and gross electrical output of 1530 MWe. The reactor employs a neutron reflector consisting of stacked stainless steel ring blocks around the core. This reflector structure improves neutron utilization and thus it lowers the fuel cycle cost. It also reduces substantially neutron irradiation to the reactor vessel and thus improves its reliability (Suzuki et al, 2009).

Safety is improved through an optimal mix of active and passive systems and enhanced redundancy. APWR's emergency core cooling system (ECCS) has a 4-train configuration instead of the conventional two trains. Moreover, the APWR utilizes an advanced accumulator system that stores borated water under pressure and it automatically injects it when the reactor coolant system (RCS) pressure decreases significantly. The system is passive in that pressurized nitrogen gas forces borated water from the accumulator tanks into the RCS. Finally, the refueling water storage pit is placed at the bottom of the containment vessel and thus it provides a continuous borated water source for the safety injection pumps during an accident.

The APWR is in the process of being licensed in Japan and there were plans to commence construction of two 1538 MWe reactors (units 3 and 4) at Tsuruga in October 2010—commercial operation of unit 3 was set to start in March 2016 and of unit 4 in March 2017. However, in October 2010, Japan Atomic Power Co announced that the construction of the Tsuruga 3 and 4 units was postponed due to delays in safety checks by the Ministry of Economy,

²² In late 2010, GEH submitted an application to the NRC to renew the certification for its ABWR technology. The original 15 year ABWR certification is set to expire in June 2012. The latest application includes a design update to reflect the current NRC requirement for an aircraft impact assessment (Nuclear Engineering, 2010a).

Trade and Industry (WNN, 2010). In 2007, Texas-based Luminant selected the US-APWR design for its Comanche Peak Units 3 and 4 south of Fort Worth.²³ And in 2010, Dominion Virginia Power announced that it selected US-APWR for a potential third nuclear generation unit at the North Anna Power Station in central Virginia.

AP-600

The Westinghouse AP-600 was one of the first Generation III reactor designs. It has a 145- assembly low-power density core, thermal rating of 1940 MWt and gross electrical output of 600 MWe. The plant can be assembled from modular components, is designed for a 60-year operating life, and is greatly streamlined. Compared with conventional reactors, it has 50 percent fewer valves, 35 percent fewer pumps, 80 percent less piping, 80 percent fewer heating, ventilating and cooling units, 45 percent less seismic building volume, and 70 percent less control cable (Nuttall, 2008a). AP-600 incorporates enhanced safety systems that rely on gravity and pressure differentials to safely shut the reactor down or mitigate the effects of an accident.

In 1999, after an extensive licensing review and independent confirmatory testing of critical systems, the NRC issued the AP-600 design certification. However, to date no orders have been placed.

Enhanced CANDU 6 (EC6)

The EC6 is a Gen III, 700 MWe (2084 MWt) class heavy-water moderated and cooled pressure tube reactor designed by the Atomic Energy of Canada Limited (AECL). It is an evolution of the CANDU 6 reactor and retains their unique feature of employing heavy water (D₂O) as a moderator to slow down the neutrons in the reactor.²⁴ The choice of D₂O as the moderator permits the use of natural uranium and allows for greater fuel cycle flexibility—e.g. recovered uranium from used LWR fuel, MOX (mix of UO₂ and PuO₂), and thorium can be used without physical modification—and independence. Moreover, such complex issues as reprocessing and enrichment can be avoided.

²³ The US-APWR is a slightly modified version of the Japanese APWR that is designed to increase electric output, comply with U.S. regulations, and meet recent utility requirements regarding safety, reliability, economy and compatibility with the environment. Improvements in the US-APWR over earlier designs include: thermal efficiency of 39 percent; a 20 percent reduction in plant building volume; and greater economy by increasing power generation capacity to the 1700 MWe class.

²⁴ Currently, eleven CANDU 6 units are licensed and operating in five countries.

EC6 includes a number of advanced passive safety features, some of which are enhancements over the safety systems in the existing CANDU plants: two independent passive shutdown systems that have been upgraded with new-engineered features to increase safety margins; a low-temperature, low-pressure moderator which can serve as a passive heat sink to absorb the decay heat in the event of an accident; a reactor vault containing a large volume of cool light water that can effectively serve as a secondary passive heat sink; a water tank located on the top of the reactor building that is capable of delivering gravity-fed, passive make-up cooling water to the moderator vessel and the reactor vault; and a thicker pre-stressed concrete structure with more reinforcing steel to achieve higher design pressure, lower leakage rate following an accident, and increased protection against external threats.

In April 2010, the Canadian Nuclear Safety Commission (CNSC) completed Phase 1 of a Pre-Project Design Review of EC6. The CNSC concluded that, at an overall level, the EC6 design is compliant with its regulatory requirements and meets the expectations for new nuclear power plants in Canada (AECL, 2010). In May 2010, EC6 was one of three reactor designs shortlisted by the Jordan Atomic Energy Commission for the country's first nuclear plant (WNN, 2011).

ANNEX B

Generation III+ Reactors

In comparison to currently operating reactors, Generation III+ systems have more robust design improvements, higher availability and longer operating life, extended fuel life, and improved and innovative safety features.

AP-1000

The Westinghouse AP-1000 is a two-loop pressurized water reactor that is an updated version of the AP600 design. The AP-1000 design has a thermal power rating of 3415 MWt and gross electrical output of at least 1000 MWe. Its fuel assembly consists of 264 fuel rods in a standard 17x17 square array, and the reactor core is designed for an 18-month fuel cycle. AP-1000 incorporates several important enhancements and employs advanced passive safety features and significant plant simplifications—it has 50 percent fewer valves, 83 percent less piping, 87 percent less control cable, 35 percent fewer pumps and 50 percent less seismic building volume than a similarly sized conventional plant—to boost safety and optimize construction, operation and maintenance. The manufacturer's goal for overall plant availability is projected to be greater than 90 percent, considering all forced and planned outages, with a rate of less than one unplanned reactor trip per year. The plant has a design objective of 60 years without a planned replacement of the reactor vessel (U.S.NRC, 2004).

The AP-1000 design incorporates major passive safety systems that require no operator action for 72 hours after the most limiting accidents—core cooling can be maintained for a protracted period without AC power. These passive safety systems include: a passive core cooling system that provides safety injection and reactor coolant from core makeup tanks, accumulators and in-containment refueling water storage tank; containment isolation provisions that are designed to prevent or limit the escape of fission products and ensure that fluid lines penetrating the containment boundary are isolated, in the event of an accident; a passive containment cooling system that consists of several components, including a natural circulation and water evaporation, that are designed to effectively cool the containment in the event of an accident; a main control room emergency habitability system that can be isolated in case of high

airborne radiation levels, and through a set of compressed air tanks maintain a habitable environment for up to 11 people for 72 hours following an accident (Cummins et al, 2003).

AP-1000 is the only Generation III+ reactor to receive design certification from the U.S.NRC—a final ruling certifying the design was issued on January 27, 2006.²⁵ It has also been certified by the European Utility Requirements. Four AP-1000 plants are under construction in China—two each at Sanmen and Haiyang—and there are current plans for additional plants to be sited in the country's coastal areas. Moreover, the AP-1000 has also been identified as the technology of choice for 14 plants that are at various stages of preparation in the United States (Sutharshan et al, 2011).

European Pressurized Reactor (EPR)

The EPR, developed by Framatome (now Areva) in France and Siemens in Germany, is an evolutionary four-loop pressurized water reactor (PWR) with thermal power rating of 4590 MWt and gross electrical output of 1770 MWe. The EPR is intended to be the world's largest reactor. Its reactor core is made up of 241 fuel assemblies with each assembly containing 65 fuel rods and 24 guide tube locations arranged in a 17x17 array. The EPR core design and its operating conditions give rise to high thermal efficiency and increased flexibility with respect to cycle length adaptations (reference cycle length is 18 months, but fuel cycle lengths up to 24 months are feasible) and thus allow for fuel cycle cost reductions through high burn-ups and low leakage loading patterns (IAEA, 2011a). There is also great flexibility for using MOX fuel assemblies in the core.

EPR's primary system, loop configuration, and main components are based on proven designs and technologies implemented in French N4 and German Konvoi PWR plants (Krugmann and Azarian, 1999). Several advanced passive features have been incorporated into the EPR design to limit radiological consequences in case of a severe accident: the sizing of the EPR reactor pressure vessel (RPV), steam generator (SG) and pressurizer (PZR) incorporates increases in the respective volumes compared to current 4-loop PWR designs—these larger

²⁵ In May 2007, Westinghouse submitted an application to revise the design in order to "aid in reducing the cost, schedule, and risk" for U.S utilities that plan to submit combined construction and operating license (COL) applications. Moreover, the company had anticipated that the decision would contribute to increased standardization of the reactor design, making the NRC's review of AP1000 COL applications more efficient (Power, 2009). In October 2009, the NRC raised concerns about the structural strength of certain components of the revised AP1000 shield building. However, in late 2011 the NRC issued a notice that the majority of its commissioners voted to certify the revised design (Bloomberg Businessweek, 2011).

volumes provide for increased thermal inertia and thus can slow the plant response to upset conditions; in addition to the standard reactor coolant system depressurization provided on other reactors, the EPR is equipped with valves dedicated to preventing high-pressure core melt in the event of a severe accident—these valves ensure fast depressurization, even in the event of failure of the pressurizer relief lines; passive catalytic hydrogen recombiners are installed inside the containment to keep the average hydrogen concentration below 10% at all times to avoid any risk of detonation in the event of a severe accident when hydrogen would be released in large quantities inside containment; a large dedicated corium spreading and cooling area outside the reactor cavity that is equipped with a solid metal structure and covered with “sacrificial” concrete—a cooling structure under the spreading area allows for extraction of the residual heat, cooling and quick solidification of the corium and an entirely passive valve arrangement allows for covering the layer of hot material and for feeding the cooling structure with water from the In-Containment Refueling Water Storage Tank located next to the corium spreading chamber; double wall containment with a reinforced concrete outer wall and a pre-stressed concrete inner wall; uninterruptible power supply ensured passively with batteries in case of station blackout and failure of all emergency diesel generators.

The Finnish electricity utility TVO signed a contract with the AREVA and Siemens consortium to build a turnkey EPR unit at the Olkiluoto site in Finland. The construction permit was obtained in February 2005. In January 2007, EDF ordered AREVA’s 100th nuclear reactor, which is being built in France, on the Flamanville site. The construction permit was awarded in April 2007. In November 2007, AREVA and CGNPC signed a contract for the supply of two EPR Nuclear Islands on the new site of Taishan in China in the context of a long-term cooperation agreement. In April 23, 2008, E.ON chose the EPR reactor as its reference design for the new nuclear power plants in the United Kingdom.

In the United States, UniStar Nuclear Energy—a joint venture holding company formed by Constellation Energy and EDF—submitted the first part of a combined license (COL) application for a US-EPR at the Calvert Cliffs site in July 2007 and the second part in March 2008. In addition to UniStar's Calvert Cliffs application, the NRC has received COL applications for three more US-EPRs: at AmerenUE's Callaway site in Missouri (application submitted July 2008 but suspended June 2009); at Constellation's Nine Mile Point site in New York (submitted September 2008 and then partly suspended); and at PPL's Bell Bend site, a new

site adjacent to PPL's Susquehanna nuclear plant in Pennsylvania (submitted October 2008). Furthermore, in June 2009, Duke Energy, Areva, UniStar Nuclear Energy, USEC, and the Southern Ohio Diversification Initiative (SODI) announced the formation of the Southern Ohio Clean Energy Park Alliance, which would investigate the feasibility of building a 1600 MWe US-EPR at the DOE's Portsmouth site in Piketon, Ohio.²⁶

Economic Simplified Boiling Water Reactor (ESBWR)

The ESBWR is the latest evolution of GE Hitachi Nuclear Energy's (GEH) proven advanced boiling water reactor technology. It has thermal power rating of 4500 MWt and gross electrical output of 1575 to 1600 MWe. ESBWR's simplified design provides for better plant safety, faster construction and lower costs, and enhanced operational flexibility. Like the GKN Dodewaard reactor, it is very simple to operate and because of the large reactor vessel and steam and water inventory, it also has a very gentle transient response. The ESBWR design relies on the use of natural circulation and passive safety features to enhance the plant performance and simplify the design. The use of natural circulation allows the elimination of several systems--recirculation pumps (and associated piping, valves, motors, and controllers), safety system pumps, and safety diesel generators (Hinds and Maslak, 2006)..

An important passive safety feature of ESBWR is the vast quantity of water to mitigate accident without operator intervention-- the water level always covers the core owing to larger in-vessel water inventory and large-capacity pools for makeup inventory, which provide improved safety margins. The remaining key passive safety systems include the following: Automatic Depressurization System (ADS)—it consists of 10 safety relief valves mounted on top of the main steam lines that discharge steam to the suppression pool, and 8 depressurization valves that discharge steam to the drywell; Gravity Driven Cooling System--the makeup water gravity flows into the vessel after the ADS depressurizes the reactor vessel; Isolation Condenser System (ICS)—it consists of four independent high pressure loops (each loop contains a heat exchanger that condenses steam on the tube side) and uses natural circulation to remove decay heat from the reactor following transient events involving reactor scram; Passive Containment Cooling System (PCCS) – it consists of four safety-related low-pressure loops (each loop has a heat exchanger open to the containment, a condensate drain line and a vent discharge line

²⁶ <http://www.businesswire.com/news/home/20110309006775/en/GE-Hitachi-Nuclear-Energy%E2%80%99s-ESBWR-Reactor-Design>.

submerged in the suppression pool) and removes heat from inside the containment following a loss of-coolant accident. The tubes of the ICS and the four heat exchangers of the PCCS are located in cooling pools external to the containment.²⁷

In March 2011, the ESBWR received a positive final safety evaluation report and design approval from the NRC thus paving the way for a final design certification. This approval gives the ESBWR 'Country of Origin' safety clearance for international construction (Business Wire, 2011). In September 2005, NuStart identified Entergy's Grand Gulf site for an ESBWR reactor. Entergy submitted the application for Grand Gulf in February 2008 and, in September 2008, submitted a further application, also referencing the ESBWR design, for its River Bend site.²⁸ In September 2008, the NRC had received two other applications: Detroit Edison submitted an application for an ESBWR at its Fermi plant in Michigan and Exelon for two ESBWR units at a new site in Victoria County, Texas.²⁹

VVER-1200

The water-cooled and water-moderated VVER-1200 reactors, designed by Gidropress, are evolutionary advanced versions of the VVER-1000 systems with thermal rating of 3200 MWt and gross electrical output of 1170 MWe. They have been developed with the aim of building a standardized Russian nuclear power plant of improved Generation III+ technical and economic performance characteristics. The goal was to meet up-to-date safety and reliability standards while at the same time lowering construction costs in an increasingly competitive generation technology market. Thus, the VVER-1200 is the main design for near term nuclear power program in Russia and for bidding in the international market (Fil, 2011).

The VVER-1200 design includes the following passive safety systems: reactor scram; core flooding; decay heat removal; containment cooling; hydrogen removal; and corium catcher. It also includes a double containment--the secondary containment system is designed to shield the reactor core from external events (e.g. an aircraft attack) and help to contain radioactivity in the event of a severe accident. VVER's passive safety systems for core cooling consist of hydro-

²⁷ General Electric-ESBWR: Technology Fact Sheet (http://www.nuclear.utah.edu/class_notes/5730/pdf/esbwr.pdf).

²⁸ However, early in 2009, Entergy announced it was reviewing its choice of reactor technology and asked the NRC to suspend its review of its COL applications until it had re-evaluated alternative technologies. The project is now suspended for several years.

²⁹ In February 2009, the NRC review of this application was suspended and Exelon then said it had chosen the ABWR design, to be built by GE Hitachi. Then, citing adverse economic conditions, Exelon withdrew its COL application and instead submitted an early site permit application in March 2010.

accumulators of the first (HA-1) and second stage (HA-2) and a passive heat removal system (PHRS). The HA-1 system provides delivery of water into the reactor for cooling and flooding of the core in case of loss-of-coolant accident (LOCA). The total inventory of water in the HA-1 systems is 200 m³, which is sufficient to ensure the required makeup of the reactor during the initial period of an accident. The HA-2 system is intended for passive supply of water into the reactor core for long-term fuel cooling during LOCA—it consists of four groups (eight tanks) of hydroaccumulators under atmospheric pressure with total coolant inventory of 960 m³. The PHRS system is intended for reactor core decay heat removal to ultimate heat sink (atmosphere) during beyond design basis accidents (e.g., station blackout). It consists of four independent circuits of natural circulation—each train has pipelines for steam supply and removal of condensate, valves, and an air-cooled heat exchanger outside the containment. Finally, a set of passive catalytic recombiners is provided to remove hydrogen from the containment.

In Russia, four VVER-1200 units are under construction (Novovoronezh II-1,2 and Leningrad II-1,2), fifteen units have been planned, and five units are being proposed.³⁰ In May 2010, the governments of Turkey and Russian Federation signed an agreement that a subsidiary of Rosatom — Akkuyu NGS Elektrik Uretim Corp.— would build, own, and operate a power plant at Akkuyu comprising four VVER-1200 units. The fuel to be used at Akkuyu would be brought from Russia, and the waste would be sent back to Russia (Turkish Weekly, 2011).

APR-1400

The APR-1400, developed by KHNP (Korea Hydro & Nuclear Power Company) and KEPCO (Korea Electric Power Corporation), is an evolutionary pressurized water reactor with thermal output of 4000 MWt and gross electrical output of 1450 MWe. It is similar to Westinghouse's System 80+ design.

The APR1400 incorporates many advanced passive safety systems. The design includes the following features: four trains of the safety injection system (SIS) with a direct vessel injection (DVI) mode and a passively operating safety injection tank (SIT); an in-containment refueling water storage tank (IRWST); and a safety depressurization/venting system (SDVS). Each SIS train has a high-pressure safety injection pump and an SIT with a fluidic device (FD) (Song et al, 2007).

³⁰ Nuclear Power in Russia (updated 18 November 2011), http://npcil.nic.in/pdf/NPP_in_Russia.pdf

In Korea, one APR-1400 unit (Shin Kori 3) is under testing, one unit (Shin Kori 4) is under construction, and there are plans for additional six units. In January 2010, a KEPCO-led consortium won a US\$20 billion tender for four APR-1400 reactors in the United Arab Emirates (Nuclear Engineering, 2010b).

Advanced CANDU Reactor (ACR-1000)

The ACR-1000, designed by Atomic Energy of Canada Limited's (AECL), is an evolutionary Gen III+ pressure tube reactor with thermal rating of 3200 MWt and gross electrical output of 1200 MWe. Its design retains many key features of the CANDU reactors, including horizontal fuel channel core, a low temperature heavy-water moderator, a water-filled reactor vault, two independent safety shutdown systems, a highly automated control system, on-power fuelling and a reactor building that is accessible for on-power maintenance and testing-- CANDU nuclear power plants use the only reactor technology designed to allow for such on-power fuelling and on-line maintenance.

The ACR-1000 design utilizes passive, stored-energy, natural circulation and gravity features for: reactor shutdown; cooling of the heat transport system when forced circulation is unavailable; core refill and fuel cooling following a loss-of-coolant accident; post-accident pressure and temperature suppression inside the containment; emergency feedwater supply to the steam generators; and mitigation of postulated beyond design basis accidents. It incorporates the following systems (the majority of which are passive) to mitigate severe core damage accidents: large thermal capacity of heavy water in the moderator and light water in the reactor vault; passive make-up to the reactor vault from the reserve water tank, including make-up from external sources; robust reactor building structure with steel liner and with large free volume; containment local air coolers; passive containment cooling spray; passive recombiners and igniters for hydrogen control; reserve water tank water recovery by the long-term cooling system (IAEA, 2011b).

In August 2007, Energy Alberta (subsequently acquired by Bruce Power) announced that it had selected Peace River as the potential site for its nuclear power plant and had filed an application for a site preparation license with the Canadian Nuclear Safety Commission. The application was for the siting of up to two of twin-unit plants, using ACR-1000 Advanced

CANDU reactors. Energy Alberta said that it planned initially to build one 2200 MWe twin-unit plant, with a start-up target of 2017 (WNN, 2008).

ANNEX C

Generation IV Reactors

Very-High-Temperature Reactor (VHTR)

The VHTR is a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle. It represents an evolution from the high-temperature reactors developed in the 1970s-1980s. Use of helium as a coolant enables the reactor core to withstand substantially higher temperatures (1000°C) relative to LWRs (300°C) and reach significantly higher levels of thermal efficiency.³¹ This allows for high temperature steam electrolysis, thermo-chemical hydrogen production, and coal gasification. Beyond electricity generation and hydrogen production, the VHTR can be used as source of very high temperature process heat for a wide variety of industrial processes. The helium gas provides a nonreactive cooling medium that adds another level of redundancy to the safety of the system. In the event of fuel cladding failure, radioactivity will be contained within the core without the risk of being transported through the coolant. Deployment is targeted for 2020, earlier than most Generation IV designs. The Pebble Bed Modular Reactor (PBMR) is a variant of VHTR.

Sodium-Cooled Fast Reactor (SFR)

The SFR is a fast-spectrum, sodium-cooled reactor with a closed fuel cycle that allows for regeneration of fissile fuel and efficient management of high-level waste (plutonium and other actinides). Its fast spectrum makes it possible to use available fissile and fertile materials (including depleted uranium) much more efficiently than thermal spectrum reactors with once-through fuel cycles. The main benefits of the SFRs relate to sustainability—actinide management to minimize the impact of radioactive waste and efficient use of fuel resources through multiple recycling. These reactors could play an important role in burning stockpiled plutonium and in reducing the volume, radio toxicity and decay heat of spent fuel (IAEA, 2011c).

Supercritical-Water-Cooled Reactor (SCWR)

³¹Helium presents significant advantages because it can be subjected to high temperature without combusting. Thus, it can facilitate the efficient transfer of thermal energy. Moreover, being an inert gas, it will not react with the VHTR materials nor become radioactive itself.

The SCWR is a high-temperature, high-pressure, water-cooled reactor that operates above the thermodynamic critical point of water (374°C, 22.1 MPa). It can operate at higher temperatures and achieve superior thermal efficiencies relative to conventional LWRs—approximately 45 percent vs. 35 percent efficiency for advanced LWRs. Since the reactor operates above the critical pressure there is no coolant boiling and the coolant remains single-phase throughout the system. It can thus transfer very large amounts of energy to the heat exchanger for steam generation. As a result, SCWR is thermally very efficient. Moreover, the need for recirculation and jet pumps, pressurizer, steam generators, steam separator plates and turbines specifically designed to deal with wet steam, is eliminated. SCWR's higher thermodynamic efficiency and the potential for considerable plant simplification lead to improved economics. These special features make the SCWR suitable for low-cost electricity generation.

Gas-Cooled Fast Reactor (GFR)

The GFR is a fast-neutron-spectrum, helium-cooled reactor with a closed fuel cycle. Its design bears a close relationship with the VHTR, and thus it is able to utilize VHTR materials and balance-of-plant technology. The reference system is a 1200-MWe reactor operating with an outlet temperature of 850 degrees Celsius using a direct Brayton cycle gas turbine for high thermal efficiency. In addition to using a direct-cycle helium turbine for electricity generation, due to the high outlet temperature of the helium coolant, the GFR can also utilize process heat for the thermochemical production of hydrogen. A key advantage of its design is that through the combination of fast spectrum and full recycling of actinides, it minimizes the production of high-level radioactive waste. Its fast spectrum allows for the efficient utilization of fissile and fertile materials (including depleted uranium)—two orders more efficiently than thermal spectrum gas reactors with once-through cycles. Moreover, the energy conversion at high thermal efficiency that is facilitated by the current design enhances the economic benefit of the GFR.

Lead-Cooled Fast Reactor (LFR)

The LFR system comprises of a fast-spectrum lead or lead-bismuth eutectic liquid metal-cooled reactor with a closed fuel cycle. A wide range of plant ratings and sizes—from small modular systems to multi-hundred megawatt sized plants—are being considered. Since the

reactor operates in the fast-neutron spectrum and employs a closed fuel cycle, it facilitates efficient management of actinides and conversion of fertile uranium. A fast neutron flux reduces substantially the generation of waste. The LFR can be used as a burner of minor actinides from spent LWR fuel by using inert matrix fuel and as a burner/breeder with thorium matrices. An important feature of the LFR is its enhanced safety that results from the choice of the relatively inert molten lead as a coolant. Moreover, the LFR system is top-ranked in terms of sustainability because of its closed fuel cycle and the fact that lead is abundant and thus available even in the case of large-scale deployment (Cinotti et al, 2006).³²

Molten Salt Reactor (MSR)

The MSR is a liquid-fueled reactor that can be used to burn actinides, generate electricity, produce hydrogen, and produce fissile fuels (breeding). Fissile, fertile, and fission products are dissolved in a high-temperature, molten fluoride salt with a very high boiling temperature (approximately 1400 °C) and circulated around a graphite moderated core. MSRs have several unique characteristics: very low quantities of long-lived actinide wastes; lower inventories of fissile materials per unit of energy and a smaller source term than any other reactor system; lower fuel costs relative to solid-fuel reactors; and large economics-of-scale. These intrinsic reactor characteristics address current concerns about radioactive waste management, fissile resources, safety, and economics. However, there are several technical challenges facing SMRs: tritium contamination of the steam cycle; freezing of the salt at low temperatures; chemical reaction between the steam and molten salts (Forsberg et al, 2004).

In view of the high capital costs and continuing investment risks (construction delays and cost overruns) of large-scale reactors and the need to service small electricity grids in many, especially developing countries, there is an ongoing effort to develop smaller reactor units. Rising concerns about large core inventories after Fukushima, and the imperative of capping the safety hazards of nuclear plants, are providing additional powerful stimulus in the search for a new, disaster-proof, nuclear reactor architecture.

³² Lead is a coolant with very low neutron absorption and moderation and consequently it is possible to maintain a fast neutron flux even with a large quantity of coolant in the core. This allows an efficient utilization of excess neutrons and reduction of specific uranium consumption. Moreover, lead is significantly more abundant (and less expensive) and hence more available relative to bismuth. In a scenario of large-scale deployment, the selection of pure lead as a coolant would offer enhanced sustainability.

ANNEX D

Alternative SMR Technologies

mPower Reactor. The Babcock & Wilcox mPower reactor is an integral pressurized-water module with a scalable, modular design that is capable of adding generating capacity in 125 MWe increments. It consists of a self-contained assembly with the reactor core, control rod drive mechanisms, reactor coolant pumps, steam generator and pressurizer placed within a single reactor vessel that is located in an underground containment. The mPower features a four-year operating cycle without refueling.

Holtec Inherently Safe Modular Underground Reactor (HI-SMUR) 140. HI-SMUR is a 145 MWe reactor whose core is located completely underground and is surrounded and supported with reinforced concrete. The reactor operates with gravity-induced flow (no reactor coolant pump) and does not rely on off-site power for shutdown. Its fuel cycle would be 3-4 years with 6 days of refueling outage.

NuScale Power Reactor. The NuScale Power Reactor is a 45 MWe natural circulation LWR design that consists of a self-contained assembly of reactor core and steam generator tube bundles within a single pressure vessel. The integrated reactor and containment vessel operate inside a water-filled pool that is built below grade. NuScale power plants are scalable, allowing for a single facility to have just one or up to 12 units.

The Westinghouse SMR. The Westinghouse SMR is a 200 MWe integral pressurized water reactor that is based on the AP-1000 design (essentially just scaled down in size). All the components typically associated with the nuclear steam supply system of a nuclear power plant are incorporated within a single reactor pressure vessel.

KLT-40S. The KLT-40S is a 35 MWe class pressurized water reactor (using seawater as coolant). It is a variant of the KLT-40, a well-established and long-proven design that has been employed in Russian nuclear powered vessels for over 20 years. The steam generators and coolant pumps are arranged as separate modules, although the whole primary system, including coolant purification and water chemistry systems, is very compact and located within the primary pressure boundary. In fact, the primary circuit design is often referred to as being leak-tight (IAEA, 2009). The exact level of enrichment for the KLT-40S has been a matter of some debate.

Initially there were plans for the reactor to run on highly enriched uranium—as is the case with the KLT-40 reactors used in nuclear icebreakers. In recent years, however, the Russian government has stated consistently that the reactors will run on low enriched uranium fuel. In June 2010, Russia launched the *Akademik Lomonosov*, a floating barge designed to carry two KLT-40S reactors (operated in pairs to avoid outages), with on-board crew living quarters, refueling capability and spent fuel storage. The refueling cycle is expected to be 3 to 4 years depending on the enrichment level of the fuel and the reactor's service life approximately 40 years.

RITM-200. This is an integral 55 MWe pressurized water reactor with forced circulation of primary coolant and external gas pressurization system. For floating nuclear power plants a single RITM-200 would replace twin KLT-40S yielding 40 MWe net (instead of 77 MWe) and requiring a barge one third the displacement. The refueling period would be 10 years (instead of about 3 years) and the service life 60 years instead of 40.

VBER-300. The VBER-300 is a 295 MWe pressurized water reactor running on pelletized uranium oxide with a gadolinium burnable poison. It is essentially an upscale of the KLT-40S offering flexible module power (depending on the number of loops) and twin unit configurations (IAEA, 2006). It was originally envisaged to be deployed in pairs as a floating nuclear power plant the first of which is planned to be built in Kazakhstan. As a cogeneration plant it is rated at 200 MWe and 1900 GJ/hr. The refueling cycle is expected to be between 3 and 6 years—with higher-enriched fuel, it could be pushed out to 15 years.

VK-300. The VK-300 is a direct cycle boiling water reactor that is being developed for both power (250 MWe) and district heating or heat for desalination (150 MWe plus 1675 GJ/hr). It has evolved from the small-power VK-50 experimental boiling-type reactor in Dimitrovgrad and its design is based on equipment components developed and manufactured for other reactor—e.g. the reactor vessel of the VVER-1000. The reactor core is cooled during normal operation and in any emergency by natural coolant circulation.

ABV reactor variants. The ABV series consists of modular water cooled integral reactors with a range of thermal capacities from 18 MWt (ABV-3) to 45 MWt (ABV-6) and corresponding electrical outputs from 4 MWe to 18 MWe. The units are compact, with an integral primary circuit design, and foresee all refueling operations to be done at the factory

(IAEA, 2007). ABV-6M utilizes a core that is similar to the KLT-40S. Its refueling cycle is around 8 to 10 years and service life about 50 years. ABV foresees all refueling operations to be done at the factory.

CAREM-25. Developed by the Argentine National Atomic Energy Commission, CAREM-25 is a modular 25 MWe (net) class reactor. Recent studies have explored the scope for scaling it up to 300 MWe. CAREM-25 has a PWR-like design with its entire primary coolant system within the reactor pressure vessel. The primary coolant flows with natural circulation from the core (at bottom) through a chimney to the upper part, then downwards through the steam generators. This natural circulation avoids the use of pumps and large diameter pipes. Its fuel is standard 3.4 percent enriched uranium with burnable poison (gadolinium) and a relatively low power density.

SMART. The Korea Atomic Energy Research Institute has been developing the System-integrated Modular Advanced Reactor (SMART), a 330 MWt pressurized water reactor with integral steam generators and advanced passive safety features. It is designed for generating electricity (up to 100 MWe) and/or thermal applications such as seawater desalination. Design life is 60 years, with a 3-year refueling cycle. There are plans to build a 90 MWe demonstration unit to

GT-MHR (Gas-Turbine Modular Helium Reactor). The GT-MHR is a 285 MWe modular high temperature, helium-cooled, graphite-moderated reactor with a direct-cycle gas turbine. It is being developed under an international cooperative program involving General Atomics, Russia's OKBM Afrikantov, and Fuji Electric. The GT-MHR uses TRISO fuel compacts in a prismatic block-type core and will utilize low-enriched U-235 as the fissile material. The power plant is essentially comprised of two interconnected pressure vessels enclosed within a below-ground concrete containment structure. One vessel contains the nuclear heat source (i.e. the reactor system) and the second vessel contains the power conversion system consisting of equipment needed for electric power generation.

ANTARES (AREVA's New Technology Advanced Reactor Energy System). ANTARES is a 285 MWe modular, high-temperature, helium-cooled reactor. It is based on the GT-MHR design. The core is sized to produce 600MW of thermal power, with a target core

outlet temperature of 1000°C for advanced electricity generation and hydrogen production applications. In 2012, ANTARES was selected by the Next Generation Nuclear Plant (NGNP) Industry Alliance as the optimum design for next generation nuclear power plants (WNN, 2012a).

Pebble Bed Modular Reactor. Like the GT-MHR, the Pebble Bed Modular Reactor (PBMR) is a modular high temperature, helium-cooled, graphite-moderated reactor with a direct-cycle gas turbine. It was until recently being developed in South Africa by a PBMR (Pty.) Ltd consortium with the participation of Mitsubishi Heavy Industries. However, due to financial difficulties and management issues, in 2010 PBMR (Pty.) abandoned all its design development activities and it currently focuses on knowledge preservation for PBMR. The PBMR and GT-MHR designs differ in terms of their fuel assembly and power rating. The 450,000 fuel pebbles that comprise the PBMR core are billiard-ball-sized graphitic spheres (60 mm diameter) containing fuel kernels composed of low-enriched (9.6 percent) uranium dioxide with TRISO coating. These fuel pebbles cycle continuously through the reactor until they are expended after about three years. Full scale PBMR production units had been planned to be 165 MWe but more recent plans call for 80 MWe power rating.

HTR. The HTR-10 is a small 10 MWt high-temperature gas-cooled research reactor intended to develop pebble-bed reactor (PBR) technology in China. It has been used to test and verify PBR safety, develop the fuel cycle, and provide experience in PBR design, construction, and operation. Construction of the HTR-PM, a larger version of HTR-10, was approved in November 2005. Site work is complete and construction commenced in mid-2011 at Shidaowan in Weihai city, Shandong province. Commercial operation is due in 2015. Initial plans called for the HTR-PM to be a single 200 MWe unit similar to the PBMR. However, revised plans call for twin 105 MWe reactors that retain the same core configuration as the prototype HTR-10. The twin units will drive a single steam turbine.

HTTR. In 1998, a small prototype gas cooled reactor—the 30 MWt High Temperature Engineering Test Reactor (HTTR)—started up at the Oarai R&D Centre. This was Japan's first graphite-moderated and helium-cooled reactor. Its core outlet temperature is 850°C and in 2004 it achieved 950°C. These temperatures will allow HTTR to be used in chemical processes such as thermochemical production of hydrogen. The HTTR is intended to establish the commercialization basis of high temperature, second-generation helium-cooled plants running at

high temperatures for either industrial applications or electricity generation. Current plans call for attaching, by 2015, an iodine-sulfur plant producing 1000 m³/hr of hydrogen to the HTTR and test the performance of an integrated production system (WNN, 2012b)

Hyperion Power Module (HPM). The HPM, designed by the Los Alamos National Laboratory, is a lead-bismuth cooled reactor with a 25 MWe rating using 20 percent enriched uranium nitride fuel.³³ It is sealed at the factory, transported in licensed cask envelope, sited underground, and eventually returned to the factory for waste and fuel disposition after a useful life of seven to ten years—i.e. there is no in-field refueling. HPM's initial application is likely to be in oil shale fields. Each HPM-based plant can be configured for steam only, co-generation or electricity only.

Power Reactor Inherently Safe Module (PRISM). The PRISM reactor is a modular, pool-type, liquid sodium cooled reactor first developed by the General Electric Company. The standard PRISM power plant design consists of three identical power blocks with a combined electrical output rating of 1395 MWe. Each power block comprises three reactor modules, each with a rating of 155 MWe and a lifespan of 60 years. Each module has its own intermediate heat transport and steam generators and is located in its own below-grade silo. The dynamics of using liquid sodium as a coolant instead of water allows the neutrons to have a higher energy that drives fission of the transuranics. The PRISM reactor consumes transuranics in used nuclear fuel from water-cooled reactors. Moreover, its design includes passive reactor shutdown and passive decay heat removal features.

EM² (Energy Multiplier Module). The EM² is a high-temperature (850°C), modular, helium-cooled fast reactor, with electrical output rating of 240 MWe. It is a modified version of General Atomic's high-temperature, helium-cooled reactor, passively safe, and capable of converting used nuclear fuel into electricity and industrial heat, without conventional reprocessing. The reactor core can burn various nuclear fuels such as depleted uranium, natural uranium, recovered uranium, LWR used nuclear fuel, thorium, low enriched uranium, transuranics, reactor-grade plutonium, and weapon-grade plutonium. The core life expectancy is approximately 30 years (consuming used nuclear fuel and depleted uranium) without refueling.

³³ In March 2012, the Hyperion Power Generation Inc. changed its name to Gen4 Energy, Inc. The HPM is now referred to as the Gen4 Module.

4S (Super-Safe, Small and Simple Reactor). The 4S reactor is a small, 10 MWe, underground, sodium fast reactor, designed by the Toshiba Corporation. Its basic layout is a “pool” configuration, with the pumps and intermediate heat exchanger inside the primary vessel. The reactor has a compact core design, with steel-clad metal-alloy fuel. It is intended for deployment in remote locations where it could operate for up to 30-years without refueling. A 50 MWe version is being examined at a conceptual level (IAEA, 2007).

BREST-300. Russia’s BREST-300 is fast neutron reactor, with 300 MWe rating, using lead as the primary coolant, at 540°C, and supercritical steam generators. It will employ a high-density, highly conductive mononitride mixed fuel which would be highly compatible with the lead and fuel cladding material (chromium martensitic steel). It is inherently safe and uses a U+Pu nitride fuel. No weapons-grade plutonium can be produced, and spent fuel can be recycled indefinitely, with on-site facilities. It should be noted, however, that the on-site reprocessing provided in the design of BREST-300 essentially limits its application in developing countries. Moreover, the designers see BREST-300 only as a prototype for a future 1200 MWe commercial BREST-1200 reactor.

SVBR-100. The innovative low-power SVBR-100 is based on the Russian technology of naval lead-bismuth cooled reactors with 101.5 MWe gross electric power rating. Its design allows the use of various types of nuclear fuel—the reference model uses enriched uranium (16.5%). It can also operate in a closed nuclear fuel cycle with mixed oxide fuel. The refueling interval is between 7 and 15 years. Moreover, the SVBR-100 has the capability of multi-purpose use: generation of electricity, desalination, and as a part of industrial plants. The current target is to build a prototype at the Scientific Research Institute for Nuclear Reactors (RIIR) in Dimitrovgrad (NEA, 2011).