THE JAMES A. BAKER III
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NEW ENERGY TECHNOLOGIES:

A POLICY FRAMEWORK FOR MICRO-NUCLEAR TECHNOLOGY

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Introduction

Energy supply and environmental challenges facing the industrialized world in recent years have rekindled interest in the expansion of electricity generation from nuclear power, but the continued development of traditional large-scale nuclear reactors for power generation has faced obstacles. Nuclear power could be a significant contributor to the long-term global sustainable energy mix, but to play this role successfully, nuclear power will have to overcome economic and political obstacles, including concerns over commercial competitiveness, nuclear waste disposal, safety and proliferation resistance.

In many countries where nuclear power plays a major role, governments are reducing their presence in the electricity generation business. Increasingly, governments are permitting market related pricing structures and ownership of generation facilities by private companies. As electricity markets become increasingly deregulated, nuclear facilities will have to compete on commercial grounds with generators using other less problematic fuel sources. The international nuclear industry is expected to find this competition increasingly daunting given the long lead times generally required for site approval and construction of nuclear power plants.

In the 44 years since the first nuclear power facility was launched, the nuclear energy industry has gone through a number of transformations. Nuclear energy currently provides about 6% of primary energy worldwide and about one-sixth of global electricity. Its contribution to energy security in Japan has been particularly significant. Through increased use of nuclear energy, Japan has been able to reduce oil use from 77% of its total primary energy mix in the 1970s to less than 55% in 2000. In the U.S., nuclear power from 103 reactors supplies 20% of all electricity generation.

There are currently 447 nuclear reactors producing electricity in 31 countries across the globe. Total capacity is 348 Gigawatts. Another 37 reactors are under construction in 12 countries, including South Korea, China and India. Japan has plans to build 13 new nuclear reactors in the coming years, but nuclear accidents, such as the major incident in 1999 at Tokaimura, have weakened public confidence in atomic power. No new reactor has been ordered in the United States for over 20 years.

The debate over development of nuclear energy came to greater prominence this year following the endorsement of nuclear power as a clean source of power by Vice President Dick Cheney in his report on U.S. energy needs. The Vice President endorsed the re-certification of all of the current 103 nuclear energy facilities operating in the U.S. to allow 20-year extensions. The 40-year operating terms of the U.S. reactors will begin expiring in 2006 and all but two will do so by 2030. The U.S. Nuclear Regulatory Commission (NRC) has already granted 20-year extensions to at least seven nuclear reactors in the last year. Vice President Cheney asserted that the development of nuclear power deserves a fresh look as the U.S. strives to reduce its dependence on foreign oil imports by increasing domestic energy supplies.

But even with the support of the Bush Administration, the question remains whether the nuclear industry can overcome the economic, social and political barriers to the continued growth of nuclear power. All U.S. nuclear reactors currently in operation are large-scale plants using tested technologies such as boiling water reactors (BWRs) or pressurized water reactors (PWRs). These facilities use low-enriched uranium fuel rods in a reactor core to create a controlled nuclear chain reaction.

However, power grids in many countries that could consider utilization of nuclear power are not large enough to support deployment of very large units. Indeed, a key characteristic of electricity markets in the 21st century will likely be a move to smaller units. Industry, government, scientists and engineers have begun to move away from the paradigm of large traditional centralized power stations and massive power grid models. Already, information technology firms are investing in co-located small or micro-power sources to meet more reliably their energy needs. Micro-turbines, fuel cells, solar panels and the like are examples of a new breed of flexibly distributed and utilized energy sources.

These new alternative energy technologies confront conventional thinking about modes of concentration or energy and its delivery and pose new competitive challenges for nuclear power.

The pace of expansion of traditional large-scale plants already appears to be slowing internationally. Several countries, including Japan, have recently announced reductions in the number of planned nuclear plants. Germany has announced the phase-out of nuclear power by 2025.

In response, new innovative designs for nuclear power deployment and utilization are under development. These designs conceptualize smaller plants that rely on passive safety systems and are more proliferation resistant. They promise that reactors could be constructed more rapidly and track actual capacity needs more closely, especially in the developing world. These new designs, it is hoped, can help nuclear power remain commercial in an increasingly competitive power-generation market environment.

To have such impact, emerging nuclear technologies will have to offer significant advantages in five critical areas: commercial competitiveness, safety, waste disposal, proliferation resistance and social acceptance. This report, based on commissioned research and a workshop convened at the Baker Institute and co-sponsored by the Petroleum Energy Center of Japan (PEC) and Lawrence Livermore National Laboratory of the U.S., investigates the merits of emerging technologies in the nuclear power field and discusses the potential of these technologies to overcome the deficits and liabilities that are increasingly blocking the growth of nuclear power. Early investigation and evaluation of micro-nuclear technologies, such as Small Innovative Reactors (SIR), can stimulate enhanced debate on future directions for research and development (R&D) that can guide work on the next generation of nuclear reactors.

The aim of this discussion is neither to endorse nuclear power nor to oppose it nor to endorse any particular plant design solution. Rather, this discussion aims to enrich the debate regarding the public policy surrounding emerging technologies for electricity generation and put forward suggestions on how to improve government participation in design and deployment of emerging technologies. An important aspect of this exercise has been to demonstrate to scientists, policy makers and public advocates the importance of public debate and participation at the earliest stages of energy technology design. Only through this kind of dialogue with broad-based participation can misconceptions be dispelled on all sides and innovations be advanced that truly respond to the needs of its constituencies—the public user of energy.

In investigating the merits of several new innovative concepts, this study on emerging nuclear technologies concludes that several micro-nuclear concepts make clear gains in several of the five critical areas but those gains are uneven and may not yet be sufficient to reverse the social and economic trends that are currently blocking the widespread growth of nuclear power. Key findings include the following:

Safety

Technologists have demonstrated conceptualization of key improvements on safety systems for next generation designs. As Greenspan and Brown discuss in their working paper, new innovative reactors reduce the chance of severe accidents by relying on natural physical phenomena rather than on proper function of mechanical and electrical components such as pumps, valves, motors and generators. With fewer pumps and valves and plant personnel required, these types of reactors would incorporate passive safety features that would respond to mitigate the worst-case scenario of radiation leakage or a plant meltdown. Because of the relatively large surface area to volume ratio of their core, SIRs are able to remove decay heat by passive means before there is a heating up of the fuel or clad to damaging temperatures. Some of these new plant designs, by not relying on mechanical or other types of pumps that force coolant to circulate, have virtually eliminated the possibility of large loss-of-coolant-accidents (LOCA) or loss of all pumps (LOFA) (see working paper, Greenspan/Brown).

But regulators and public interest advocates raise several questions about whether existing SIR designs really resolve adequately safety concerns surrounding nuclear power. The new SIR designs, which involve small, highly pressurized containments, do not eliminate the possibility of failure in the containment structure or problems that may arise from a degradation of materials, leaking pins or other kinds of leaks. Moreover, autonomous systems can also fail or problems can arise with the fuel, says Ellis Merschoff, Administrator for Region 4 of the U.S. Nuclear Regulatory Commission (NRC). "Designs must plan for failure of components of the plant. If we look at the problems at existing plants, the most expensive problems have been the ones that no one ever imagined would have to be fixed," he notes. "There is a need for maintainability as well as proliferation resistance."

It would also not be possible to fully test the fuel by heating it to extreme levels, creating a heavy reliance on testing at the theoretical modeling level. Given these and other factors, social acceptance might be low for new designs that do not allow for on-site inspections of the core during its operation, notes Ed Lyman, scientific director of the Nuclear Control Institute in Washington D.C.

Proliferation Resistance

The design of SIRs specifically addresses the concerns of proliferation potential. There are several attributes that make them more proliferation resistant than conventional, large-capacity nuclear reactors. As discussed in the working paper by Greenspan and Brown, these include: low frequency of refueling, restricted access to fuel, restricted access to neutrons, and elimination of the need by the host country to construct facilities that could be used for clandestine production of strategic nuclear materials. In several designs, the high burnups employed also lead to the generation of plutonium with an isotopic mix that significantly complicates its use in weapons.

But, no new reactor designs can be said to be proliferation proof. Advantages gained by very high burn-up rates can easily be obviated by operation at lower burn levels though this itself can raise other obstacles in terms of total volume of material needed. Additionally, over time, the decay of the fission products will lower the radiation barrier of spent fuel, while the decay of PU-238 will make it easier to use the extracted plutonium for weapons.

Finally, as discussed in the working paper by Feiveson, the new reactor designs would use uranium that is more highly enriched than in current reactors, though still far from weapon-grade. This means that a potential proliferant, if uranium was successfully obtained, would require less separation work for production of weapons grade uranium than for ordinary light water uranium fuel (see working paper by Feiveson).

Some designs, such as SIR hub-spoke concepts, propose to cluster all sensitive nuclear facilities in centralized, heavily-guarded nuclear parks, perhaps under international control. Long-life reactor cores would be assembled at the central facility, imagined either as an international center or a center located in a "safe" and stable country with established nuclear power programs. The reactors would be sealed, and then exported to users in other countries where it could be "plugged in" to the remainder of the electric generation system. After some years (say, 15), the core/spent fuel would be returned to the central facility or to some international spent fuel repository. During the 15 years of operation, there would be no re-fuelling. In such a system, a country would need relatively few research facilities, operators, and other trained nuclear technicians and engineers.

Such international energy parks would clearly offer advantages over existing operating systems from the point of view of proliferation resistance. Practically speaking, however, the hub spoke concept may be politically difficult to implement.

Commerciality

A key advantage to SIR designs is that their modularity may reduce the cost of building nuclear energy systems by shortening the extensive time now required for on-site construction, assembly and equipment installation at traditional plants and by allowing plant size to be increased gradually to meet customized needs of clients. While construction times on conventional large-scale nuclear plants usually run four to five years in the best of circumstances, it is projected that the smaller units as reflected in the SIR designs could be built within roughly similar on-site construction time as gas turbine power systems which can be built in less than one year. This can be accomplished because SIR's smaller size, more integrated designs and modularity permit much of the fabrication and assembly work to be conducted in the factory – providing a standard unit with the ability for unit pieces to be mass-produced.

Proponents believe substantial cost savings can be realized from this more rapid installation and possibly from lower decommissioning costs. As discussed in the working paper of Schock, Brown and Smith, passive safety systems, few refueling shutdowns, increased automation and higher fuel burnup rates could also bring reduced operation and maintenance costs. But others, such as Stanford University economist Geoffrey Rothwell, note that economy of scale advantages can only be replicated by producing many plants. Pilot projects will be needed to reduce the economic penalty of creating a factory just to make one plant. The chicken/egg problem of the manufacturing facilities for each module will, nonetheless, stand as a barrier to entry. In addition, cost estimates for the new designs, while on paper competitive, have yet to be verified by demonstration and operating experience. Experience in the development of the nuclear industry has shown that unexpected additions to operating costs cannot be ruled out.

Waste Disposal

Virtually whatever the reactor technology, waste disposal challenges will be daunting. If nuclear power were to become the electricity fuel of choice in line with the high-demand scenario of the Intergovernmental Panel on Climate Change (IPCC), worldwide capacity would rise to 6500 Gwe. If this total capacity were based on a once-through fuel cycle using light water reactors, it would generate roughly 1200 tons of plutonium annually (see working paper by Feiveson). If based on liquid-metal plutonium breeder reactors, it would involve the fabrication into fresh fuel annually of over ten thousand tons of plutonium. Given plausible burn-up rates, the spent fuel generated annually could hardly be less than about 50,000 tons –equivalent to one Yucca Mountain repository being constructed roughly about every 18 months.

Social Acceptance

To gain social acceptance, a new technology must be beneficial and demonstrate enough trouble-free operation that people begin to see it as a “normal” phenomenon. Nuclear energy began to lose this status following a series of major accidents in its formative years. As argued in the working paper by Michael Golay, acceptance accorded to nuclear power may be trust-based rather than technology based. In other words, acceptance might be related to public trust of the organizations and individuals utilizing the technology as opposed to based on understanding of the available evidence regarding the technology. Golay questions the entire concept that social acceptance of nuclear power can be gained through the creation of demonstrably safer technologies.

While the U.S. nuclear industry has seen well over a decade or two of seemingly trouble free operation that demonstrably shows up in improved polling statistics for public acceptance, nuclear power's global experience does not mirror this trend. Continued problems in Japan and the former Soviet Union continue to fuel worries, and in some cases, anti-nuclear sentiment abroad, raising questions about whether nuclear energy can realistically register strong growth in the developing world.

It has been speculated that nuclear power might gain more of a public constituency in the future because it provides electricity in a manner that reduces greenhouse gases and other emissions.

At present, nuclear power worldwide generates approximately 2200 billion kWh per year. As discussed in the working paper by Feiveson, were this amount of electricity generated instead by coal plants, an additional quantity of carbon dioxide containing 550 million metric tons of carbon would be emitted to the atmosphere each year. This is about 8.5% of total carbon emissions from fossil fuel combustion (6500 million tons per year). But if this electricity were generated by natural gas, the extra carbon emitted by the gas plants would be about two-fifth of the 550 metric tons noted above, or 220 million tons per year, a contribution of only about 1.5 percent to total extra carbon emitted over the coming thirty years. In the very long run of 50 to 100 years, nuclear power could play a bigger role in reducing greenhouse gases but not decisively so.

Background: The Backdrop to Innovation in the Nuclear Industry

The first commercial nuclear energy-powered facility in the U.S. went into operation at a site on the Ohio River in Shippingport, Pennsylvania in 1957. By 1970, there were 90 nuclear power plants operating in 15 countries, including 15 in the U.S.

But it was during the 1970s that the use of nuclear energy mushroomed worldwide, with construction beginning on an average of 25 to 30 nuclear-powered plants each year. By 1980, there were 253 operating nuclear-powered plants with 135,000 megawatt-electric (MWe) total capacity in 22 countries. In the 20-year period between 1973 and 1993, in the U.S. alone, nuclear power created as much energy as 2.1 billion barrels of oil, 2.6 billion tons of coal, and 9 trillion cubic feet of natural gas combined.

Growth in the nuclear power industry has stalled in the industrialized West over the past two decades for a variety of reasons. A slowdown in economic growth in the aftermath of the 1970s oil crises curbed the growth in electricity demand in many Western markets. In addition, in the U.S. and Europe, availability of natural gas at competitive prices also promoted the advancement of combined cycle generation plants as an alternative to nuclear energy. Also, major accidents such as those at Three Mile Island, Chernobyl and Tokaimura, combined with shifting social preferences, have led to a weakening in public support for nuclear power.

The growth in nuclear power in Western Europe could potentially slow in the coming years, with political pressures emerging in several countries. France has the largest nuclear program in Western Europe. The French government, recognizing its limited domestic fossil fuel resources and wanting to guarantee a high level of energy security, began its nuclear energy program in earnest in 1974. Today, nuclear power provides France with almost 80% of its electricity needs, and the country is largely self-sufficient in all phases of its nuclear fuel cycle. But, public support for nuclear energy has begun to wane in France. In April 1996, the French government unnerved the nation when it began handing out iodide tablets to people living close to nuclear plants. Then, in January 1997, a medical journal reported higher than average leukemia rates near the Cogema nuclear processing plant in Normandy. The facility came under further scrutiny in January 1999 when a judge called for a formal investigation into allegations that it was illegally storing nuclear waste.

But the most awkward moment for the French government was its February 1998 announcement that it was shutting down the $10 billion Superphenix fast-breeder reactor, which had been perceived as a key component of the French nuclear program. Built in 1976, the Superphenix was to have been the world's largest fast-breeder reactor with a 1,240 MWe capacity. It was from the outset, however, bedeviled with problems and only produced six months worth of electricity over 12 years of operation. The plant was first shut down in July 1990 after a string of leaks from its cooling system. The reactor was restarted in 1994, but only for research purposes.

More recently, a number of politicians, including French Prime Minister Lionel Jospin, have begun voicing the possibility of reducing the country's dependence on nuclear energy. In January 2001, Jospin's government suggested that France should cut its dependence from the current levels of over 75% to around 60% over the next two decades.

In the U.K., where 25 reactors provide the nation with approximately 25% of its electricity, the nuclear power generation program has effectively been stalled since 1987. Much of the U.K.'s nuclear generating capacity was privatized in the late 1990s. The country is involved in all stages of the nuclear fuel cycle and remains a leader in nuclear technology design. Although Prime Minister Tony Blair's Labour government pledged in the run-up to its 1997 election victory that it would not promote the building of new nuclear plants, it did not repeat that promise before its land-slide victory in June 2001. Blair set a storm of controversy in motion on June 26, 2001, when he hinted that an expansion of nuclear power capacity would be examined as he launched the country's first energy review in 20 years.

Some West European countries, like Italy, rejected nuclear energy development early on, while a 1980 national referendum in Sweden called for the phasing out of the country's 12 nuclear power plants. However, only one plant has been closed since that referendum, and the country faces a difficult task of eliminating nuclear power that currently accounts for about 50% of Sweden's electricity.

The rise of the environmentalist Green party in Germany has speeded up the country's plans to transition away from nuclear power. In early June of 2001, German Chancellor Gerhard Schroeder whose Social Democratic party came to power in a coalition with the Green party in 1998, signed a plan that would shut down the country's last nuclear reactor by 2025. Germany's 19 reactors provide about one-third of the country's electricity generation and the government has said it will look to environmentally friendly energy resources to replace nuclear power while remaining committed to reducing greenhouse gases. With coal already providing 50% of Germany's electricity needs, Schroeder's government favors renewable energy sources, such as wind power or solar cells, as replacement for nuclear energy.

There are currently 68 nuclear reactors operating in Eastern Europe and the Former Soviet Union, of which 29 are in Russia, supplying 15% of its electricity; 13 in Ukraine, supplying 47%; six each in Bulgaria (45%) and the Slovak Republic (53%), five in the Czech Republic (20%), and the remainder in Hungary (41%), Lithuania (74%), Armenia (33%), Romania (11%) and Slovenia (37%). Nearly all of the nuclear reactors are Soviet-designed.

The Russian government has stated that it plans to build 40 new reactors over the next 20 years, but skeptics say that Moscow will have a difficult task in financing such a large-scale expansion. Although Russia and Ukraine have both expressed interest in the idea of storing the West's nuclear waste, doubts remain about the safety of their reactors and storage sites. Russia recently said that at least 15 nations would be willing to pay Moscow to store their nuclear waste at a massive site it plans to build in Siberia. Moscow has also said that it is considering selling uranium abroad.

The prospects for nuclear power in Asia are seen as more promising than in the West. Electricity demand in Asia is expected to increase three-fold with some forecasts putting electricity usage in the area within the next two decades expanding by as much as 130%.

Asian governments are keen to enhance their civilian nuclear energy capacity for a number of reasons, including reduced dependence on foreign energy sources, improved air quality, reduced greenhouse gas emissions, and access to nuclear technology for military purposes.

Air pollution in a majority of Asian urban centers remains a significant problem for the region, exceeding levels in most cities in North America and Europe and greatly surpassing World Health Organization guidelines. In China and India, in particular, where there is a heavy dependence on coal, urban air quality problems are extensive. Nuclear power is seen as one vehicle for easing air pollution and acid rain levels. China, for example, which has three nuclear reactors that account for just 1.2% of the country's total power output, currently has another eight under construction.

The Asian drive towards nuclear power is not without its problems, nonetheless. Many Asian countries must rely on imported uranium to operate their reactors and do not have the fabrication and enrichment services that are provided from the outside, raising a host of other questions that go beyond the energy security benefits of diversifying away from oil or the air quality benefits of moving away from heavy reliance on coal. Some of the Asian nations are working to expand the domestic content of their nuclear fuel cycles by building facilities for fuel enrichment, fabrication and reprocessing, as well as looking to invest in overseas uranium mines and locking up long-term enrichment contracts.

South Korea has 16 nuclear reactors that currently provide 41% of the country's electricity supplies. The country relies on Europe, Russia and the U.S. for its enriched uranium needs, while Korean firms provide nuclear power expertise and equipment to others, including China, Vietnam and Turkey. South Korea has four new reactors under construction.

Japan is the regional leader in nuclear capacity, operating 52 reactors that provide roughly 34% of the country's electricity needs. Tokyo's nuclear fuel cycle has been expanded to include fuel enrichment and fabrication facilities at the front end, and the capability to employ reprocessing and recycling facilities at the back end. While independent in plant operation, design and maintenance, Japan is reliant on uranium imports.

Faced with mounting public opposition, the Japanese government in late 1999 cut back its goal of building 20 new nuclear reactors by 2010, reducing the number to 13. Indeed, a handful of accidents in the 1990s, notably a major incident on September 30, 1999 at a uranium reprocessing facility in Tokaimura, have undermined previously strong Japanese public confidence in atomic power. The criticality accident at the Tokaimura facility was caused when workers ignored safety procedures and mixed several times the maximum safe amount of uranium in buckets, setting a nuclear chain reaction in motion. Two workers died as a result of serious radiation poisoning, while several hundred were exposed to abnormal radiation levels.

Public opinion polls carried out in the months following the incident reflected an increasing loss of trust in the Japanese government's nuclear energy policy. On May 28, 2001, Japanese Prime Minister Junichiro Koizumi urged his government to redouble efforts to win public support for nuclear energy, one day after voters in the northern town of Kariwa rejected plans to use recycled plutonium – plutonium-based mixed oxide or (MOX) – in a large nuclear facility there. Koizuma stressed the need for Japan to develop its nuclear fuel-recycling program.

New Designs: Overcoming Past Obstacles

In a sign that the potential for expanding nuclear power electricity generation is not being ruled out by key governments, eight countries on July 24, 2001, signed a former charter establishing the Generation IV International Forum (GIF), which will be dedicated to the development of next generation nuclear power reactor and fuel cycle technologies by 2030. The nations that inked the accord were the Argentina, Brazil, Canada, France, Japan, South Korea, the U.K. and the U.S.

Spencer Abraham, the U.S. energy secretary, described the agreement as a foundation for the U.S. and its partners to develop innovative nuclear energy technologies that would be safer, more reliable, and more economical.

In the next several decades, a substantial increase in electric power demand is expected to emerge in the developing world as economic progress allows a wider number of communities to attain electrification. At present, more than 2 billion people live without the benefits of electric power. The large rise expected in the number of electricity generation plants in operation worldwide has raised environmental concerns that mass consumption of fossil fuel will lead to lower air quality and a large jump in emission of greenhouse gases. Nuclear power remains a potential solution but new designs may be necessary to adapt to changing commercial and social requirements. While the existing generation of nuclear reactors will continue to play a major role for the next decade or so, the future rests with new fourth generation designs that might be able to provide safer, more reliable nuclear power through smaller, modular units that will better conform to commercial needs and competitive pressures.

The recent report on the Geopolitics of Energy, released by the Center for Strategic and International Studies and chaired by former U.S. Senator Sam Nunn and former Department of Energy Secretary James Schlesinger, listed three essential conditions for nuclear-power reactors to be suitable for use in developing countries: they must be modular with a generating capacity of about 100 Mwe, they must be cost-competitive with fossil-fuel power plants, and they must be proliferation-resistant.

The International Atomic Energy Agency (IAEA) estimates that, by 2015, there will be a substantial market in developing countries for small and medium-sized nuclear reactors in the range of 50 to 300 Mwe. A still greater market is expected over the next fifty years. South Korea, China, Argentina, and Japan, among others, are developing reactors to fill this projected need (see working paper by Schock/Brown/Smith).

In response to the changing market and social requirements, nuclear power companies have instituted design changes that are intended to enhance safety. Already, three companies -- General Electric (GE), Westinghouse Electric and ABB Combustion Engineering -- have won approval from the U.S.'s Nuclear Regulatory Commission (NRC) for a new generation of reactor designs. The commission's pre-approval of these designs means that if a plant is ordered, opponents will not be able to challenge their construction on safety grounds. Instead of using mechanical pumps to deliver cooling water to the hot reactor core, the Westinghouse AP-600 uses a passive design, with cooling water stored in tanks right above the reactor. In case of an accident, gravity would activate the release of thousands of gallons of specially treated water into the reactor container. Westinghouse claims that its AP-600 requires 35% fewer pumps and 50% fewer valves, 70% less cable and 80% less piping than conventional reactors, thereby reducing the chance for equipment failure.

Fourth-Generation Reactors

In addition to these approved new designs, a number of fourth-generation reactor concepts have been developed over the past decade. These designs, expected to come into play after 2020, aim to address the shortcomings of the traditional and newer larger scale unit designs. Research and development have focused on making the reactors smaller with a reduced number of components and a simpler design that would produce a more simplified operation and maintenance. Generation IV research and development found support from the Nuclear Energy Research Initiative (NERI) government program which was initiated following the recommendations of the U.S. President's Committee of Advisors on Science and Technology in 1997.

The NERI program seeks to enhance the technical development potential and prepare infrastructure, such as human resources and demonstration research, to maintain U.S. capability in future nuclear technologies.

The Most Popular SIR Designs

For the purposes of this report, we discuss several fourth generation design ideas that are under investigation. This list is by no means exhaustive but covers a range of proposed ideas that are further along in the development process than others. Table 1 provides a sketch of the various characteristics of various SIR concepts, organized by type of cooling fluid.

Among the most advanced new innovative designs under investigation are: the International Reactor and Secure Nuclear Power System or (**IRIS**) – a unique pressurized water reactor (PWR) concept with steam generators integrated within the reactor pressure vessel; the Pebble Bed Modular Reactor (**PBMR**) – a modular graphite-moderated helium (He)-cooled reactor that employs a direct-cycle gas turbine (GT); the **4S** -- a sodium-cooled modular fast-reactor that is designed to operate for up to 30 years without refueling; and the Encapsulated Nuclear Heat Source Reactor (**ENHS**) -- a modular Pb-Bi (lead-bismuth) or lead-cooled reactor designed to function as a "nuclear battery", as it is shipped to the site fueled and then replaced by a new module after 20 years of full power operation.

Each of these four reactor designs strives to simplify plant operations by reducing the number of components and the facility's capacity. The IRIS design integrates the steam generators, coolant pipes and pressurizer within the reactor vessel, thereby eliminating large piping loops that connect these parts. That, in turn, reduced the probability of large loss-of-coolant accidents (LOCAs). Its Nuclear Steam Supply System (NSSS) can be designed to be significantly more compact and housed in a containment of a substantially smaller volume.

The PBMR design for a graphite-moderated He-cooled high temperature reactor envisions using a GT power plant to convert the fission-generated thermal energy to electricity. The idea is that it is possible to greatly reduce the number of components and the overall size of the power plant by replacing a conventional steam power plant with a direct-cycle GT power plant. Another benefit of switching to a GT power plant is that the bulk of the construction work is performed in the factory, with a shorter fabrication time and higher thermodynamic efficiency. The PBMR design would, by pumping helium heated in the reactor core directly to the gas turbine, eliminate the need for a traditional second coolant system that is used in steam-powered systems, thereby substantially reducing the capital cost of the plant. The PBMR makes use of TRISO-coated fuel particles in billiard-ball sized graphite "pebbles" that continuously flow into and out of the core reactor zone.

Table 1. Summary of Small Innovative Reactor Characteristics.

Characteristic	Light-Water-Cooled		Gas-Cooled		Liquid-Metal-Cooled			Other Concepts	
Concept	Westinghouse IRIS[a]	So. Korea SMART[b]	Eskom PBMR[c]	GA/Russian MHTGR[d]	Japan 4S [e]	UC Berkeley ENHS[f]	Argonne Star-LM[g]	Molten-Salt[h]	Heavy Water[i]
Development Status	Pre-conceptual design	Conceptual design	Conceptual design	Conceptual design	Conceptual design	Pre-conceptual design	Pre-conceptual design	No design activity	No design activity
Power (MWth/MWe)	300/100	330/90	230/100	600/280	125/50	125/50	300/100	350/155	?/100
Inlet temp, °C	292	270	490	490	430	430	292	550	280
Outlet temp, °C	330	310	800	850	550	550	550	700	320
Operating pressure, MPa	15	15	7.0	7.1	0.1	0.1	0.1	0.1	15
Fuel	UO_2 or MOX	UO_2 or MOX	UO_2 or MOX graphite pebbles	UO_2 or MOX graphite blocks	U and U/Pu metal	U and U/Pu metal	U metal	U fluoride salts	UO_2 or MOX
Refueling, yr	7	2	On-line	2	30	>15	15	On-line	On-line
Power conversion	Steam turbine	Steam turbine	He gas turbine	He gas turbine	Steam turbine	Steam turbine	Steam turbine	Gas turbine	Steam turbine
Reactor vessel size, m	18 x 4.4	9.8 x 3.9	25 x 9	25 x 7.3	23 x 2.5	19 x 3.2	14 x 5	8 x 12	Pressure tube

[a]Mario Carelli, et al., "IRIS Reactor Development," *9th International Conference on Nuclear Engineering*, April 8–12, 2001, Nice, France.

[b]Ju-Hyeon Yoon, et al., "Design Features of SMART for Barge-Mounted Application," *Propulsion Reactor Technology for Civilian Applications*, IAEA Advisory Group Meeting, Obninsk, Russia, 20–24 July 1998, IAEA-AG-1021.

[c]www.pbmr.co.za/2_about_the_pbmr/2_about.htm

[d]Utility/User Incentives, *Policies and Requirements for the Gas Turbine Modular Helium Reactor*, General Atomics, September 1995, DOE-GT-MHR-100248.

[e]Y. Nishiguchi, et al., "Super-Safe, Small, and Simple Reactor Concept Toward the 21st Century," *Proceedings of the Workshop on Proliferation-Resistant Nuclear Power Systems*, Center for Global Security Research, Lawrence Livermore National Laboratory, June 1999.

[f]E. Greenspan, D. Saphier, D.C. Wade, J. Sienicki, M.D. Carelli, L. Conway, M. Dzodzo, N.W. Brown, and Q. Hossain, "Promising Design Options for the Encapsulated Nuclear Heat Source Reactor," submitted to ICONE-9 (2001).

[g]B.W. Spencer, et al., "An Advanced Modular HLMC Reactor Featuring Economy, Safety, and Proliferation Resistance," *8th International Conference on Nuclear Engineering*, Baltimore, Maryland, April 2–6, 2000.

[h]K. Furukawa, et al.," Small Molten-salt Reactors with a Rational Thorium Fuel Cycle," *IAEA Second International Seminar on Small and Medium Sized Reactors*, San Diego, California, August 21–23 1989.

[i]R.S. Hart, "The CANDU 80," *Proceedings of an IAEA Advisory Group Meeting on the Introduction of Small and Medium Reactors in Developing Countries*, Atomic Energy of Canada Ltd., Canada, IAEA-TECDOC-999, February 1998.

The intent of the 4S design is to vastly reduce the size and scope of a large-size sodium-cooled fast reactor through a number of structural changes, including: the elimination of the upper core structure by using reflector segments instead of control rods; the use of only a few simple drives for control and safety rods; the elimination of the concrete neutron shield at the structure roof by taking advantage of the thick sodium layer above the reactor core; and the reduction of required emergency power by relying on decay heat removal by natural circulation. Toshiba has designed a variation of the 4S reactor, referred to as L4S, that uses lead-bismuth (Pb-bi) instead of sodium (Na) and eliminates the second NA coolant loop altogether. For that reason, the L4S is considered to be significantly more compact with fewer components than the 4S version. However, since sodium is very active chemically, inspection and maintenance of this design may be more difficult.

Another design is the ENHS that would not have any fuel-handling hardware nor any pipes or valves in the inner chamber. The ENHS module is placed in the center of the secondary coolant vessel, with eight steam generators surrounding the module. As both the primary coolant – which is located in the ENHS module – and the secondary coolant – located in the reactor pool – flow by natural circulation based on the laws of physics, there is no need for mechanical devices or pumps that would traditionally force the coolant to circulate. Another advantage – which truly sets this design apart from the other three – is that the fuel is loaded into the ENHS module in the factory, and the module is designed for full power operation without on-site refueling.

One of the features inherent in the ENSH concept of no on-site refueling is that at the end of its core life, around 20 years, the entire reactor module is replaced. The spent module is returned to a recycling facility to be disposed of or recycled. This innovative design feature eliminates on-site refueling and therefore the risk of refueling accidents. It also minimizes the opportunities that the facility can be used to garner weapons grade materials (see Greenspan/Brown).

Proliferation Concerns

A major argument stated against the widespread use of nuclear energy is that some countries might employ the development of nuclear energy as a cover for the development of nuclear weapons. Similar concerns exist that reprocessing or refueling operations leave open the risk that weapons-grade plutonium and highly enriched uranium could be stolen or sold to adversarial sub-national or national groups. SIR developers have attempted to make their designs more proliferation-resistant than the conventional large-capacity reactors of the past four decades.

All existing power reactors use either natural uranium or low-enriched uranium fuels that cannot be used for weapons purposes. However, the nuclear process in the reactors does generate plutonium that could be used for weapons. The plutonium is formed in uranium-based reactors through neutron capture by the uranium-238 isotope. However, in once-through fuel cycles in which the spent fuel is not reprocessed, the plutonium always remains mixed with the highly radioactive fission products and cannot be used for weapons without further processing. In these circumstances, there are formidable barriers to the diversion of plutonium:

- The spent fuel assemblies are massive.
- They are highly radioactive.
- They would have to be processed in heavily shielded facilities in order to separate out the plutonium.

But, in those countries that reprocess their spent fuel – involving the separating out of usable products like plutonium and uranium to run again in the reactor – the separated plutonium can be a proliferation danger. Flows of separated plutonium can be difficult to measure and monitor. One year's spent fuel from a large power reactor contains enough plutonium to make over 50 nuclear bombs. There has, however, never been a reported incident of an individual or group that has diverted separated plutonium from a civilian reactor to use for military purposes.

The U.S. has discussed the purchase 500 tons of highly-enriched uranium recovered from dismantled Russian nuclear weapons after the uranium is blended down to low-enriched uranium for reactor fuel. The U.S. and Russia have also stated intentions to dispose of 34 tons of plutonium recovered from the dismantled weapons, but so far, no agreements have been finalized.

Meanwhile, Washington has expressed its opposition to Russia's assistance to several other countries' nuclear programs, including Iran's Bushehr nuclear power facility and India's Tarapur power plant. The latter facility receives its fuel from Russia. In 1995, Russia signed a $780 million contract with Iran, as well as an agreement in September 1998 to complete construction on the Bushehr nuclear facility within 52 months. The 1995 contract with Russia calls for completion of two, 1,300-MWe pressurized-light water units as well as the supply of two modern VVER-440 units.

In the case of India, the Tarapur reactors near Bombay are under IAEA supervised safeguards, but some of India's other nuclear facilities are not. Washington has pointed out that Russia, as a member of the Nuclear Suppliers Group, was required to not cooperate with the nuclear programs of any country that did not accept comprehensive safeguards on all of its nuclear facilities. New Delhi, which carried out nuclear tests in 1998, has declared itself a nuclear power and has vowed to press on with building a nuclear deterrent.

The design of the SIRs specifically addresses the concerns of proliferation potential. The ENHS module design, for example, is designed to be factory fueled and to be disposed of, or recycled, after 20 years of full power operation. It is envisioned that the ENHS factories and possibly co-located recycling facilities would incorporate stringent international safeguards and security controls. The fuel is to be sealed inside the ENHS module from the time the module leaves the factory until the spent module is returned to the waste disposal site or to a regional or international recycling center. It is planned that the ENHS power plants will not even have on-site hardware for refueling. Moreover, the large size of the ENHS module and that fact that its fuel is shipped embedded in solid lead-bismuth or lead would make it extremely difficult to divert. In addition, because the fuel is loaded in the factory before shipment, there is the possibility that the core could be seeded with a strong source of Gamma rays, enhancing the radiation barrier.

The pebble-bed modular reactor derives its proliferation resistance from the fact that the spent fuel would be high burn-up material in thousands of tiny carbon-coated spheres making it a comparatively unattractive source from which to recover weapons-usable materials. At any given time, the core of the reactor (nominally 110 MWe) would consist of 360,000 pebbles (60 mm in diameter), each containing about 7 grams of uranium (in the fresh fuel) in 11,000 microspheres (0.9 mm diameter). While the total content of the plutonium could be as high as 5 kilograms per ton of uranium fuel, this means that as many as two hundred thousand pebbles would have to be diverted to obtain a critical mass (see working paper by Feiveson).

Advocates of the gas-cooled reactor and ENHS claim that neither reactor requires research reactors to train people to run such plants safely, reducing the chances of a host country using nuclear power programs to develop military applications.

It has been proposed that the ENHS reactor design would not provide the client country with sensitive technologies that could be used for clandestine production of strategic nuclear materials since no fuel fabrication or handling facilities are needed in the country. The ENHS and other SIR designs can boast that they can offer the client country long-term energy security due to the very long life cores they can have without the need to acquire fuel enrichment and spent fuel reprocessing capabilities.

Such programs would, instead, cluster all sensitive nuclear facilities in centralized, heavily-guarded nuclear parks, perhaps under international control. This is what is imagined in some of the SIR (or, hub-spoke) concepts. Long-life reactor cores would be assembled at the central facility, imagined either as an international center or a center located in a "safe" and stable country with established nuclear power programs. The reactors would be sealed, and then exported to users in other countries where it could be "plugged in" to the remainder of the electric generation system. After some years (say, 15), the core/spent fuel would be returned to the central facility or to some international spent fuel repository. During the 15 years of operation, there would be no re-fuelling. In such a system, a country would need relatively few research facilities, operators, and other trained nuclear technicians and engineers.

Politically, international energy parks, while arguably reducing proliferation risks, run against the strong wish of many countries to utilize nuclear power specifically to be energy independent. Moreover, countries may be reluctant to accept the idea of importing sealed nuclear reactors while eschewing any effort to develop a domestic cadre of nuclear engineers and scientists. At least some nuclear research facilities will be needed, since 200-metric-ton units will have to be shipped through the importer's port cities and coastal locations. Moreover, the "nuclear battery, wheel-spoke" concept will require either that client countries accept discriminatory restrictions on its nuclear activities not accepted by the countries hosting the nuclear parks, or that all countries, including the industrialized countries, accept a high degree of international control of their nuclear energy programs (see working paper by Feiveson). Finally, many developing world countries look to power grid development as a means to create employment for their nationals. The nuclear battery wheel-spoke concept will not generate many jobs in the host country.

Facing The Cost Challenges

Several factors propelled the advancement of large-scale nuclear power plants in the 1970s. Investment risk was minimal under electricity rate regulation, and the operating costs and overall cost per unit of electricity generated by large-scale nuclear power (greater than 600Mwe size units) appeared competitive with available alternatives of the time. Public acceptance was relatively high, and timely construction of plants could be predicted. And, finally, all externalities were not included in power costs, including disposition of spent fuel, decommissioning costs or unanticipated accident mitigation costs.

Today, the trend toward rate-deregulation in generation markets in many countries has created a more risky environment for large-scale nuclear power investments. Large front-end investment is no longer protected by government rule-making and intervention in markets. Industry no longer enjoys the benefits and predictability of government set prices that guaranteed profits or highly subsidized waste disposal costs. Site permitting costs have also become unpredictable. Thus, nuclear power plant today faces a number of economic challenges in competing with other fuel-driven plants (see working paper by Taylor).

Over the past two decades the U.S., following on the heels of a number of Western European nations, began deregulating its power industry. The degree of implementation of deregulation in the U.S. varies by region. By the same token, much of the power industry in Western Europe is undergoing a transition from state ownership and government control to private ownership and open markets. Membership terms for joining the European Union (E.U.) have served as a central driving force behind deregulation in Europe. In the U.S. by contrast, deregulation is following a decentralized pattern of varied state-by-state implementation. The E.U. deregulation plan targets 30% of each member country's market to be opened by 2000, and then 35% by 2003.

The U.K., Sweden, Norway and Finland have already opened 100% of their electricity markets to competition. Denmark is expected to reach that goal by 2002, while Germany, the Netherlands and Austria are not far behind. By 2003, it is estimated that 80% of the 15-member E.U. will be deregulated. France is the least liberalized national market and maintains considerable state control to this day.

A host of Asian countries – Bangladesh, Cambodia, China, Hong Kong, India, Indonesia, Japan, Malaysia, Pakistan, the Philippines, Singapore, South Korea, Taiwan, Thailand and Vietnam – are involved in varying stages of power privatization. These countries are closely watching deregulation policies in other areas of the world.

Where capital costs are written off as a sunk cost, the marginal cost of electricity from existing U.S. nuclear plants are presently lower than coal-, gas- and oil-fired plants, while renewables, except for hydro, are currently operating with substantial subsidies. The present market advantage for nuclear exists because the capital investments in most existing nuclear plants have for the most part been written off as "stranded costs" as part of the move toward deregulation.

Table 2: Average Electricity Production Costs
(cents/Kwh, 1999 dollars)

Year	Nuclear	Coal-fired	Gas-fired	Oil-fired
1995	2.10	2.05	2.93	4.12
1996	2.04	1.94	3.59	4.40
1997	2.36	2.17	3.63	3.95
1998	2.18	2.12	3.37	3.31
1999	1.83	2.07	3.52	3.18

Source: Nuclear Energy Institute, UDI

Since the investment in a new large conventional power plant cannot be written off, its relative economic advantage evaporates because of its high amortization costs. Assuming natural gas prices will follow projected escalation trends, the cost of electricity from gas-fired plants continues to be the market benchmark to which small innovative nuclear reactors will have to meet.

Gas-fired plants at $400/KWe and wind-powered plants at $800/KWe have a substantial advantage in capital cost as compared to coal at $1,000/KWe, nuclear at $1,480/KWe, and renewables ranging from $1,400/KWe to $2,550/KWe. Gas-fired plants are projected to maintain their economic advantage on the assumption that gas prices will follow predictable escalation trends. The cost of electricity from gas-fired plants continues to be the market benchmark that all the alternative generators are striving to meet (see working paper by Taylor).

The following tables compare the capital costs of new conventional nuclear, coal and gas-fired plants as well as a variety of renewable fueled plants. Capital costs are converted to costs/kwh via a projected capital recovery factor (see working paper by Taylor).

Table 3: Overnight Construction Costs of Coal, Nuclear, Natural Gas, and Renewables
($/Kwe)

	Year of Startup			
Type	**2005**	**2010**	**2015**	**2020**
Nuclear	1600	1480	1400	1380
Coal	1080	1000	900	860
Natural Gas	450	400	380	360
Wind	800	800	800	800
Photovoltaic (flat plate)	3000	1500	1400	1080
Bio-Mass (gasification)	1520	1400	1300	1200
Large Hydro	1800	1700	1650	1600
Solar Reflector (power tower)	2300	2550	2500	2500

Table 4. Cost of Electricity From Coal, Nuclear, Natural Gas, and Renewables

(cents/Kwh)

		Year of Startup		
Type	**2005**	**2010**	**2015**	**2020**
Nuclear	4.8	4.5	4.4	4.3
Coal	3.5	3.3	3.0	2.8
Natural Gas	3.2	3.1	3.0	2.8
Wind	3.0	2.8	2.7	2.6
Photovoltaic (flat plate)	15.0	8.0	7.0	6.0
Bio-Mass (gasification)	6.0	5.5	5.0	4.5
Large Hydro	5.8	5.5	5.3	5.0
Solar Reflector (power tower)	12.5	8.0	7.5	7.0

(Levelized cost of electricity estimates based on the efficiencies, book lives, capacity factors, and capital, operating and maintenance, and fuel costs pertinent to each system; EIA gas cost projections.)

A modern coal-fired power plant costs $1.50 per watt to build and 1 cent to 1.5 cents per kilowatt-hour (kWh) to operate. A small gas fired aero-derivative turbine plant costs 60 cents per watt to build and 3.8 cents per kWh to operate. A large modern nuclear plant costs between $1.50 to $2.00 per watt to build and around 1 cent to 2 cents per kWh to operate. This is the arena in which small nuclear plants will have to compete. The commercial designers of the PBMR claim that a 110-MWe module can be built and operated cheaper than these options.

In general, proponents of small reactors argue that countervailing factors will compensate for losses in economies of scale. These factors include simpler reactor control and refueling systems and modular construction and factory fabrication. Operating costs should be lower because of higher fuel burn up leading to reduced fuel costs and smaller volumes of waste, fewer refueling shutdowns, increased automation and consequent reduction in staffing, and simpler decommissioning. However, unknown added expenses may be expected in shipping a fully fueled reactor and installing it at the site (see working paper by Schock/Brown/Smith).

Previous approaches to nuclear power economics relied on "economies of scale" -- the larger, the cheaper per unit of power. For small reactors, economics must be approached from a different perspective: they must rely instead on the economics of mass production, coupled with cost savings achieved from factors including substantially reduced on-site installation, operation and decommissioning costs; reduced site infrastructure requirements; and substantial improvements that will streamline the licensing process.

While the regulatory framework has been improved by the NRC and the present operating nuclear plants have indeed benefited from rate deregulation, the higher capital cost of new nuclear plants could remain a barrier to market entry. In the new rate deregulated market, not only the rate but also the rapidity of return is important. While the Advanced Light Water Reactor (ALWR) program has made substantial progress in reducing capital costs, the progress has not been significant enough to enable these types of reactors to effectively compete with gas-fired generation at gas prices around $3.00 per million British Thermal Unit (BTU). The question thus arises whether SIRs through their improved design and modularity, can offer a viable competition to gas-fired power plants.

A busbar generation cost analysis demonstrates that both the PBMR and the IRIS have a potential economic advantage over the ALWR designs. However, cost estimates for plants at a relatively early stage of development tend to reflect economic goals and have not yet been tested by actual construction. Estimates of uncertainties are needed to address this. Using conventional economic techniques such estimates indicate that the IRIS and PBMR cost projections range from 10 to 15% above normal contingency provisions as compared to 2 to 65 for ALWRs. Although the ranges analyzed are greater for the smaller modular reactors than for the ALWRs, they still reflect a reasonable level of confidence in the cost projections. On the other hand, the uncertainty analysis does not include the cost impact of “unknowns,” including technical design uncertainties. Here, the ALWRs have an advantage since their technology has been proven, is certified by the NRC and costs are taken from actual experience.

TABLE 5: Busbar Generation Costs

(cents/Kwh)

Plant Type:	**AP-600**	**AP-1000**[(a)]	**IRIS**	**PBMR**[(b)]
Power (MWe):	2x600	1x1090	3x333	10x110
Busbar Cost (cents/Kwh):				
Capital	2.6	1.8	1.4	1.7
O&M	0.8	0.55	0.6	0.3
Fuel[(c)]	0.6	0.6	0.35	0.47
Decommissioning	0.1	0.1	0.1	0.1
Total:	4.1	3.05	2.49	2.63
"Overnight" Capital Cost ($/KWe)	1485	1075	636	1004

(a) GE is developing a 1000 MWe passive BWR, called the ESBWR, which shows similar economic potential.

(b) ESKOM has reported total bus bar cost estimates ranging from 1.7 to 2.4 cents/Kwh

(c) Includes 0.1 cents/Kwh for used fuel disposition.

How To Handle The Waste Issue

The greatest advantage of nuclear power is the ability to pull out a tremendous volume of energy from a small volume of fuel compared to other types of power plants. One metric ton of nuclear fuel produces energy equivalent to two million to three million tons of fossil fuel. While fossil fuels annually generate hundreds of thousands of metric tons of gaseous, particulate and solid wastes, nuclear systems produce less than 1,000 metric tons of high and low-level wastes per plant per year. Although the high-level waste is intensely radioactive at first, it can be isolated and contained. Spent nuclear fuel loses radioactivity but only extremely slowly over time.

But, the management of nuclear waste and spent fuel has bedeviled the industry since nuclear energy was first used commercially. The volumes of radioactive waste and spent fuel are rising. Although most of the waste is intermediate and low-level and it is believed that this waste can be disposed of in properly licensed sites and safely managed, the management of high-level and long-lived waste and spent fuel is much more daunting. Some nations use the "once through" cycle, meaning that all spent fuel is considered waste even though re-usable uranium and plutonium exists. "Once through" spent fuel is typically stored temporarily at the reactor site in specially designed water-filled pools. Although these pools were designed to provide temporary storage, many countries, like the U.S., that employ the "once through" cycle have yet to select permanent disposal sites.

In recent years, given the political difficulties of identifying permanent disposal sites, nuclear reactor operators have been forced to expand the capacity of on-site storage pools by re-racking or packing the rods more efficiently. When, after a period of time, the heat from the rods lessens, they can be stored outside of the water pools in containers such as metal or concrete storage casks. Not all U.S. reactors have dry storage at their facilities. The Nuclear Energy Institute, the U.S. industry's main trade organization, reports that there are 16 sites with dry cask storage and an additional 20 will run out of space in their spent fuel pools by the end of 2004 and will need similar storage options. Nearly all of the country's 103 reactors will need additional storage by 2010. It costs more than $1 million for enough casks to store one year's worth of fuel for one reactor.

Nearly 20 years ago, most of the U.S. nuclear reactor operators signed a contract with the federal government for the Department of Energy (DOE) to take the fuel to a proposed permanent waste facility in Nevada for burial, beginning in January 1998. Because the government fell short on its promise and was unable to take the spent fuel, 12 utilities sued the DOE to recoup their costs after the 1998 deadline. The reactor operators had been paying the government one-tenth of a cent per Kwh generated, in exchange for the government promise to take the fuel. Most of the operators ended up settling with the government, with the DOE agreeing that the plants could skip payments equal to the price of the casks.

The operators are eager to have the DOE take the spent fuel off their hands, preferably to a federal burial site or at least to a centralized above-ground repository. The DOE has spent nearly $6 billion to research and test a deep geological site in the remote desert at Yucca Mountain in Nevada. The nuclear industry has contributed $16 billion into the nuclear waste fund that will pay for developing and operating the repository. But, environmental concerns, including questions about possible earthquakes at the site and the safety of routinely hauling the material cross-country, have prevented its approval during the last two decades. Senate Democrats in the current Congress, including Senate Majority Whip Harry Reid of Nevada have made it clear they will not agree to any proposal to designate the location a permanent waste disposal site.

The Yucca option has been the only one that the U.S. government has considered as a permanent waste site. If built, the repository would rest 1,000 feet underground in a massive volcanic rock formation. The water table is another 1,000 feet below that. Scientists, however, disagree on whether the site would be stable for the envisioned 10,000-year storage period. Even under the best circumstances, Yucca would not be ready to begin receiving waste materials until 2010. And, even if the Yucca Mountain site were to open, it is too small. Under the 1982 Nuclear Waste Policy Act, the permanent disposal site is supposed to accept 77,000 tons of civilian and military wastes, but the civilian wastes will end up being more than that, in part because of license renewals, which were not anticipated 20 years ago.

In contrast to Japan, France and the U.K., the U.S. has not actively pursued reprocessing. In the 1977, Washington instituted a policy prohibiting the recycling of commercial nuclear fuel. President Jimmy Carter signed the original directive in response to concerns that recycling was not economical and to fears that it would create a market for plutonium that could be supplied for nuclear weapons proliferation efforts elsewhere after President Ford had placed a moratorium on reprocessing pending further study. The U.S. only reprocessing plant in West Valley, New York, operated for a few years in the 1960s, but was a technical and financial failure. Carter barred a second plant from opening. The DOE estimated in 1999 that it would take $280 billion to develop reprocessing technology in the U.S.

In reprocessing, uranium and plutonium can be recycled in the reactors, thereby extending the use of the original fuel and reducing the volume of waste for permanent storage. The recovered plutonium is recycled in the form of MOX fuel. There are three MOX fuel fabrication plants operating in Europe that supply 30 reactors with MOX fuel in Belgium, France, Germany and Switzerland.

There are estimates that France, the world leader in recycling since it started using the process in 1958, produces about a kilogram (kg) of recycled fuel for about $6,000, while a kg of low-enriched uranium plutonium like that used in U.S. reactors costs about $1,200. One of the consequences of high cost of MOX fabrication is that over the years, the world has accumulated about 210 tons of commercial – and weapons-usable – plutonium that does not have a market. In traditional reprocessing, spent fuel is dissolved in acid, separating the uranium, plutonium and other fission products. The fission products are encased in glass and stored. The plutonium is recombined with uranium 238, made into rods and put into reactors. This is what is called MOX fuel (mixed oxide) and essentially substitutes plutonium 239 for the fissile uranium 235 in first-generation fuel. A presidential directive by former U.S. President Bill Clinton extended the 24-year moratorium on a domestic MOX reprocessing cycle because of the proliferation risks associated with isolating plutonium 239.

The International Atomic Energy Agency (IAEA) has estimated that, as of the end of 1999, some 75,000 metric tons of the 220,000 metric tons of spent fuel produced over the last 40 years, has been reprocessed and 145,000 metric tons are being stored in wet or dry facilities. Given today's reprocessing capacities, by 2010 more than 230,000 metric tons of spent fuel will be stored and 110,000 metric tons will have been reprocessed.

Although a handful of nations have embraced reprocessing as a way to extend their fuel sources and reduce hazardous waste materials, it has not been without cost and controversy. In February 2000, the U.K. was rocked by reports that British Nuclear Fuels PLC (BNFL) had falsified quality control data on reprocessed nuclear fuel supplied from its Sellafield plant to customers in Japan and Germany. The revelation led to the resignation of BNFL's chief executive. Although BNFL had promised to ship the fuel in question back to the U.K. and pay its customers compensation, the Japanese power companies delayed negotiations.

The Japanese community of Kariwa dealt the Sellafield plant a further blow in May 2000 by voting in a referendum to reject plans to use MOX in the nearby Kashiwazaki-Kariwa power plant. Because Japan was to provide more than 40% of the Sellafield plant's revenue, the U.K. facility is in trouble, as it cannot get an operating license from the U.K. government until doubts about its economic viability are removed. BNFL had already been hit by the German government's decision to end reprocessing of its spent nuclear fuel by Sellafield. German utilities were Sellafield's second largest customer after Japanese firms. The German government has decided that temporary storage facilities will be built near the country's nuclear reactors to handle the waste problem.

Meanwhile, France was hit hard by the German decision as its Le Hague reprocessing plant relies upon German spent fuel for about 40% of its business. Although the German government had moved to cancel the French and U.K. reprocessing contracts, it ended up negotiating and agreeing to continue to send the spent fuel to the foreign plants for recycling during the next four to six years that it will take to build the temporary storage facilities. But the fallout from the Sellafield scandal was even more pervasive, as Sweden and Switzerland pulled out of reprocessing contracts with BNFL in 2000.

Japan has seen the costs of reprocessing soar, with the cost of recycling its nuclear spent fuel more than double what the alternative, dry storage, costs. The transport of spent fuel to Europe and nuclear waste back to Japan adds to the cost advantage of dry storage in Japan. In the past, Japanese utilities had not found the cost arguments against reprocessing compelling; as regional monopolies, they had been able to pass the higher costs onto the electricity users. However, with the highest electricity prices of the member countries of the Organization for Economic Cooperation and Development (OECD), the Japanese government was prompted to begin deregulating the electricity industry, putting pressure on companies to lower costs.

Following the 1970s oil crisis, the Japanese nuclear industry pressed the government to accept the fact that fast breeder reactors (FBRs) that would burn plutonium separated by reprocessing spent fuel would ultimately make Japan independent of other countries for its energy needs. However, an accident at the Monju fast breeder research reactor in December 1995 that involved a massive sodium leak prompted the Japanese government and energy utility officials to reconsider pursuing FBR technology. Critics complained that FBR technology was uneconomic, technically difficult and politically unpopular. Burning MOX fuel in existing Japanese reactors has also proved difficult, as MOX costs several times more than new uranium, and there is a concern in the country about keeping MOX secure from terrorism.

Several factors have converged to create a surplus of plutonium. Firstly, expansion of nuclear energy has proceeded slower than originally expected. Moreover, disassembly of nuclear weapons under post-Cold War agreements, combined with the increasing volumes of plutonium from reprocessing operations of spent fuel, has created a surplus of plutonium, lowering its price and raising security risks. At the same time, it is now known that reprocessing and plutonium fabrication costs are more expensive than originally believed, leaving the industry's profitability in question. With little evidence that uranium might be in short supply any time soon, the urgency for Japan to continue to develop its FBR program has waned. Rather, the new circumstances have created a need for fast combustion reactors that can quickly consume plutonium (in contrast to breeder reactors that can create it).

Japan continues to position the FBR cycle as central to its nuclear strategy, but is opening the way for change. The report "Long-Term Program on Research, Development and Utilization of Nuclear Power" published by the Japanese Atomic Energy Commission in November 2000 notes "…it is important for the fast breeder reactor and related nuclear fuel cycle technology… to be able to improve uranium utilization efficiency…and to be developed with a steady effort with a view of securing a potent option for future energy supplies in anticipation of unpredictable conditions in the future" (see working paper by Suzuki).

Significantly, therefore, the report considers the FBR cycle not as an absolutely necessary energy source but rather as just one of the promising energy options for the future and the pursuit of varied research and development of more than one technology option is endorsed. A subcommittee wrote in a later commentary: "…it is necessary for the state, industry and universities to cooperate in studying R & D for innovative reactors, taking into consideration use of a variety of ideas, regardless of the reactor's size or design" (see working paper by Suzuki).

Despite this change in stated policy, many issues remain to be addressed in Japan before a varied program can be fully implemented. First, changes must be made in the existing budget allocation system. More than half of Japan's nuclear power R&D budgets are allocated to Japan Nuclear Cycle Development Institute (JNC), which is, by the law, restricted to "FBR and nuclear fuel cycle R&D and related R&D." This rigidity limits the amount of funding that can be channeled to development of innovative nuclear reactors. Resistance remains against designs based on once-through cycle technology. Other rigidities in the specific government institutions that control the budget for research funds might also be suitably reformed to promote innovation in Japan's nuclear industry (see working paper by Suzuki).

Considerable momentum exists in Japan to simply continue to utilize the large-scale light-water reactor regime that is already tested and for which businesses and infrastructure already exists. However, if international trends shift to favor development of innovative technologies, Japan will be under increasing pressure to respond to innovation and reform its R & D agenda.

Already, in the 1990s, the nuclear industry has entered an era of extensive international reorganization wherein firms have merged with companies from other countries, creating multinational nuclear corporations. For example, BNFL of the U.K. acquired Westinghouse and ABB of Switzerland while French-owned Framatome announced integration with Siemens of Germany. The number of firms overall has been reduced, and development of new technologies is focusing not on national strategic policy but rather on multi-national partnerships and to a growing extent, international cooperation. This could give way to an "option sharing" approach where rather than narrowing the range of technological options at the level of a country or company, risks are dispersed by pursuing many technologies at once. Results of multinational projects then will be shared, with each nation participating benefiting from access to developing technological innovation and securing long-term competitiveness (see working paper by Suzuki). However, this approach will find resistance in many countries including the U.S. in certain circles that hold an underlying belief that sharing of scientific knowledge can damage national security.

Gaining Social Acceptance

To gain public acceptance, a new technology must be beneficial and demonstrate enough trouble-free operation that people begin to see it as a "normal" phenomenon. Nuclear energy began to lose this status following a series of major accidents in its formative years. The turning point was 1979 following an accident at the Three Mile Island (TMI) plant near Middletown, Pennsylvania. The TMI accident stimulated sweeping changes involving emergency response planning, reactor operator training, human factors engineering, radiation protection, and many other areas of nuclear power plant operations. It also caused the NRC to tighten and heighten its regulatory oversight.

Today, the TMI-2 reactor is permanently shut down and defueled, with the reactor coolant system decontaminated, the radioactive liquids treated, most components shipped to a licensed low-level waste disposal site, with the remainder of the site being monitored. The owner, General Public Utilities Nuclear Corporation, says it will keep the facility in long-term storage until the operating license for the TMI-1 plant expires in 2014, at which time both plants will be decommissioned.

The causes of the accident continue to be debated to this day. However, based on a series of investigations, the main factors appear to have been a combination of personnel error, design deficiencies, and component failures. There is no doubt that the TMI accident permanently changed both the American nuclear industry and the NRC. Public fear and distrust increased, NRC's regulations and oversight became broader and more robust, and management of the plants was scrutinized more carefully. The problems identified from careful analysis of the events during those days have led to permanent and sweeping changes in how NRC regulates its licensees -- which, in turn, has strengthened public health and safety.

Failure of the cooling system of the No. 2 nuclear reactor at the TMI plant led to overheating and partial melting of its uranium core and production of hydrogen gas, which raised fears of an explosion and dispersal of radioactivity. Thousands living near the plant left the area before the 12-day crisis ended, during which time some radioactive water and gases were released. Detailed studies of the radiological consequences of the accident have been conducted by the NRC, the Environmental Protection Agency, the Department of Health, Education and Welfare (now Health and Human Services), the DOE, and the State of Pennsylvania. Several independent studies have also been conducted. Estimates are that the average dose to about 2 million people in the area was about only about 1 millirem. To put this into context, exposure from a full set of chest x-rays is about 6 millirem. Compared to the natural radioactive background dose of about 100-125 millirem per year for the area, the collective dose to the community from the accident was very small. The maximum dose to a person at the site boundary would have been less than 100 millirem.

In the months following the accident, although questions were raised about possible adverse effects from radiation on human, animal, and plant life in the TMI area, none could be directly correlated to the accident. Very low levels of radionuclides could be attributed to releases from the accident. However, comprehensive investigations and assessments by several well-respected organizations have concluded that in spite of serious damage to the reactor, most of the radiation was contained and that the actual release had negligible effects on the physical health of individuals or the environment.

While the TMI incident was a turning point for the growth of nuclear energy in the U.S., it paled in comparison to the 1986 Chernobyl accident, the implications of which reverberated around the world. The disaster at the Chernobyl nuclear power plant in Ukraine was the product of a flawed Soviet reactor design coupled with serious operating mistakes. The four reactors at Chernobyl were RBMK-1000s, Soviet-designed and built graphite moderated pressure-tube type reactors employing slightly enriched uranium dioxide fuel.

The accident destroyed the Chernobyl-4 reactor and killed 30 people, including 28 from radiation exposure. A further 209 on site were treated for acute radiation poisoning and among these, 134 cases were confirmed (all of whom recovered). Nobody off-site suffered from acute radiation effects.

However, large areas of Belarus, Ukraine, Russia and beyond were also affected to varying degrees. The radioactive clouds were blown towards northern Europe. Seventy percent of the radiation was estimated to have fallen on Belarus with serious repercussions.

While both the TMI and Chernobyl incidents were seminal events in turning public opinion against the use of nuclear energy, there are theories that suggest that changing times and cultural perceptions were also a strong influence in how the public perceived nuclear energy. For example, one theory posits that, since its inception, nuclear power has gone through three eras of social acceptance in the U.S. (see working paper by Golay).

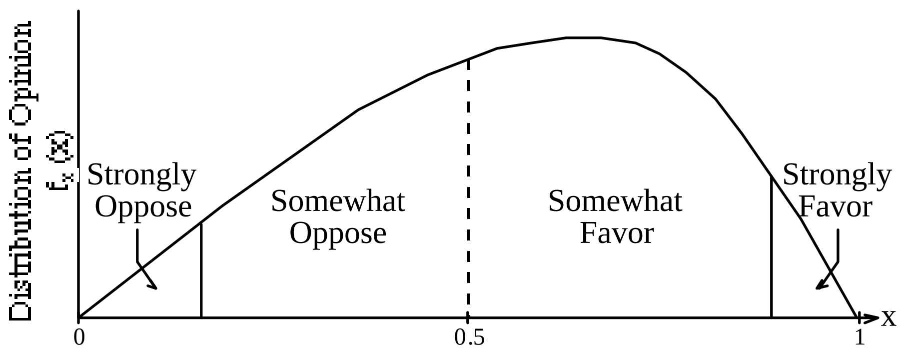
The first era, the Eisenhower and Kennedy years before 1968 and the Vietnam War, was when nuclear power was viewed as a prestigious and highly favored technology within U.S. society generally. Schemes for nuclear powered airplanes and rockets were supported generously, and serious universities wanted their own research reactor. It was during this time that the orders for most of the currently operating nuclear power plants were placed or planned.

The tide began to turn against nuclear power following a slowdown in economic growth in the years following the Vietnam War, responding to the accompanying drop in the growth in electricity demand (see working paper by Golay). Nuclear technology came under vigorous attack as an important symbol of the military establishment against which the anti-war movement developed. Negative cultural attitudes developed against weapons and industrial waste and these spread to nuclear energy even prior to the accidents at TMI and Chernobyl. As proliferation expanded, nuclear weapons became a more frightening prospect and with that came anxiety about nuclear power reactors (see working paper by Golay). A USA Today poll in April 1986 put only 36.3% of respondents believing the U.S. should continue to build nuclear power plants in the U.S. while a Harris poll asking the same question in September 1973 found 64% of respondents favored continued construction of nuclear power plants in the U.S.

In the last era, the early 1990s to the present, a period of sustained economic expansion in the U.S. helped boost national confidence and optimism. The result has been to diminish, to an extent, concerns about various perceived threats, including those of nuclear power. This situation has been bolstered by steady improvements in the operational record of the U.S. nuclear power plants and the possibility that these existing nuclear plants can provide competitively priced electricity. Indeed, the low frequency of events in the U.S. that could cause public alarm has led to a lessening of both interest in and frequency of nuclear power-related stories in the media.

Polling data for the U.S. for the last decade or so reveals that most people do not hold strong positions concerning nuclear power, indicating that it is relatively unimportant to them. Using essentially the same questionnaire, Bisconti Research, Inc. has tracked public opinion in this area for the Nuclear Energy Institute over the past 12 years. Results have been fairly constant.

Figure 1. Population Distribution of Opinion Concerning the Acceptability of Nuclear Power.



x = approval rating for nuclear power (x > 0.5 indicates approval, x = 1 indicates total approval, x = 0 indicates total disapproval, x = 0.5 indicates indifference)
f = distribution function of nuclear power approval rating within population

Function Shape Depends Upon
- Sense That Nuclear Power is Beneficial
- Recent Nuclear Power Operational Track Record

Moreover, an ABC-Harris Survey shows a slight improvement in the position of nuclear power, with 81% of Americans finding nuclear power very safe or somewhat safe in March 1999, as compared with only 67% in April 1979.

Ironically, the U.S. experience with nuclear power is not mirrored in some other countries with large nuclear energy programs. In Japan, public confidence in the country's nuclear power program has been severely undermined in the past decade, starting with the December 1995 sodium leak at the Monju fast breeder research reactor and the more serious September 1999 accident at the Toikamura uranium reprocessing facility. The belief in a high degree of safety and trust in the Japanese nuclear power industry may have evaporated with the Toikamura accident, as the Japanese public perceived that not only was it a terrible fatal mistake, but it was an "accident waiting to happen" (see working paper by Kotler).

Government opinion polls throughout the 1980s and 1990s showed that a majority of Japanese found nuclear power plants "safe" or "somewhat safe." This allowed officials to ignore localized public protests against the plants. Arguments promoting nuclear power to enhance energy self-sufficiency overrode arguments over its dangers, even after occasional accidents at nuclear power plants highlighted safety risks. But political and social changes occurring in Japan in the mid to late-1990s have shifted public opinion against pro-nuclear government policies. Political and economic upheaval coupled with numerous scandals involving bureaucrats and politicians have eroded public trust in the government. These factors have lead to stronger calls for policy reform (see working paper by Kotler).

By the 1990s, several accidents at Japan's public and private nuclear facilities posed serious threats that could have been potentially damaging to the entire nation. International criticism of management of Japan's nuclear program became pronounced. Although government promises were made after each incident to ensure public safety and expand information access, the very same issues reemerged as factors in new accidents.

A February 1999 Prime Minister's Office poll on energy also provided evidence of continued Japanese public ambivalence on nuclear energy. The poll found that 42.7% of respondents thought that the number of nuclear power plants should increase, while 27.2% thought the status quo should be maintained, and 21.4% thought nuclear power plants should be abolished. When asked about concerns regarding nuclear power generation, however, 68.3% of respondents said they felt worried about Japan's nuclear power generation, while only 25.4% said they felt at ease. Thus, while a majority of Japanese (69.9%) support the existence of nuclear power, an almost equal majority (68.3%) were worried about the effects of using nuclear power generation.

Public opinion polls conducted in the months immediately following the Tokaimura accident showed a loss of trust in the Japanese government's nuclear energy policy. In an October 1999 *Asahi Shimbun* poll taken shortly after the criticality accident, 42% of respondents disagreed with supporting nuclear power, while 35% agreed. Another poll conducted in November 1999 by Mainichi Shimbun found that 53% of people have feelings of distrust regarding the Japanese government's nuclear energy policy, while 38% have feelings of trust for it.

A local poll conducted by the Toikamura government planning section at the end of 1999 demonstrated that the number of respondents supporting nuclear power after the accident fell to 32.2% from 52% before the accident. But, those calling for the discontinuation of its usage rose from 11.7% to 40% after the accident. In addition, the number of respondents who said that nuclear power facilities are unsafe after the Toikamura incident was 78.2% (see working paper by Kotler).

Can Nuclear Make A Major Contribution to Reducing Global Warming?

It has been argued that the rise of the environmental movement and the accompanying commitment to environmental goals, including lowering global greenhouse gas emissions, will increase the constituency for nuclear power and enhance its social acceptance. Indeed, nuclear power could be a significant contributor to the long-term global sustainable energy mix and provide electricity in a manner that reduces greenhouse gases and other emissions.

However, the role of nuclear power in reducing greenhouse gas emissions could be quite limited for the next several decades. This is partly because nuclear power does not at present appear suitable for a role outside the electricity sector (even if eventually it could become important for desalination, process heat, and hydrogen production). The emissions of carbon worldwide in both the electric and non-electric sectors are expected to be considerable. According to the principal business-as-usual demand scenario (IS92a) of the Intergovernmental Panel on Climate Change (IPCC), total carbon emissions from the energy sector are expected to grow from today's 6.5 billion tons to 13 billion tons in 2050, with total cumulative emissions of carbon through 2050 of 440 billion tons (see working paper by Feiveson).

At present, nuclear power worldwide generates approximately 2200 billion kWh per year. Were this amount of electricity generated instead by coal plants, an additional quantity of carbon dioxide containing 550 million metric tons of carbon would be emitted to the atmosphere each year. This is about 8.5% of total carbon emissions from fossil fuel combustion (6500 million tons per year). The comparable amount of carbon avoided by virtue of nuclear power in the U.S. is 155 million tons (see working paper by Feiveson).

Annual Carbon Emitted and "Saved" Today Worldwide Millions of tons Carbon		
	Coal (0.25 kgC/kwh)	Gas (0.10 kgC/kwh)
Carbon Saved Nuclear	550	220
Total Carbon Emitted	6500	6500

To look at matters the other way round, were nuclear power to be phased out, the loss in carbon savings would be less since the replacement for nuclear would be not coal, but natural gas in combined cycle power plants (so long as natural gas remains in high supply). In this case, the extra carbon emitted by the gas plants would be about two-fifth of the 550 metric tons noted above, or 220 million tons per year.[1] Theoretically, were such a phase-out of nuclear power to take place over 30-years, the total extra carbon emitted would be 3.3 billion tons, out of a total of 225 billion tons expected to be emitted worldwide during that period – about 1.5 percent.

Cumulative Carbon to 2000-2030 w and w/o Nuclear Phaseout (billion tons Carbon)	
Extra Carbon if Phaseout	3.3
Total Carbon Emitted	225

If worldwide nuclear power could grow at just over 2%/year until 2050 to an installed capacity in that year of 1000 Gwe,[2] it would lead to cumulative avoided carbon emissions about 36 billion tons – roughly 8% of the total cumulative carbon emissions projected during this 50 year period[3] (see working paper by Feiveson).

[1] Natural gas emits about 15 kg C/GJ compared to 25 kg C/GJ for coal; and the efficiency of gas turbines is about 50% compared to 35.5% for coal. This means that the carbon emitted by a modern gas plant is approximately 0.1 kg/kwh.
[2] I realize that a steady growth over the next 50 years is unlikely. If anything growth might be slow or even negative for a while and then take off. So this is just a back-of-envelope calculation.
[3] Carbon avoided is calculated on basis of 0.175 kg carbon avoided per kwh. This is roughly equivalent to that if there were not the indicated nuclear power growth, one-half of the alternative electric capacity would be from coal-fired plants and one-half from gas turbines. The cumulative avoided emissions are for the 21st century.

In the very long run, nuclear power could play a more significant role if it reached say 50-75% of global-installed power after 2050 as projected in the high-demand scenario of the IPCC. The installed nuclear capacities associated with these projections are 3000 Gwe in 2075 and 6500 Gwe in 2100, roughly a ten-fold and twenty-fold expansion from today.[4] In these circumstances, the total carbon emissions avoided cumulatively would be approximately 290 billion tons through 2100. The latter would be one-fourth the projected cumulative carbon emissions to 2100 of 1150 billion tons – significant, though not decisive (see working paper by Feiveson).

Cumulative Carbon Emitted and "Saved" Next 100 Years
Billions of tons Carbon

	To 2050	To 2100
Total Carbon Emitted (IPCC)	440	1150
Carbon Saved Nuclear (0.175 kg/kwh)	36 1000 GW in 2050	290 6500 GW in 2100

That the impact of such a robust nuclear future on global warming would be so limited is sobering, since the management of a nuclear system with the capacities considered above would be truly formidable. For example, a worldwide capacity of 6500 Gwe, if based on a once-through fuel cycle using light water reactors, would generate roughly 1200 tons of plutonium *annually*. If based on liquid-metal plutonium breeder reactors, it would involve the fabrication into fresh fuel annually of over ten thousand tons of plutonium. Virtually whatever the reactor technology, given plausible burn-ups, the spent fuel generated annually could hardly be less than about 50,000 tons – equivalent roughly to one Yucca Mountain repository being constructed roughly every 18 months (see working paper by Feiveson).

[4] The IPCC high-demand variant corresponding to the IS92a projections shows approximate total primary energy as follows: 360 exajoules in 1990, 420 EJ in 2025, 660 EJ in 2050, 970 EJ in 2075, and 1350 EJ in 2100. By 2050 and thereafter, electricity is assumed to be about one-half that of total primary energy; and nuclear electricity 40% of total electricity in 2050, 50% in 2075, and 75% in 2100. The total non-nuclear primary energy associated with these data is 358 EJ in 2000, 460 EJ in 2025, 609 EJ in 2050, 777 EJ in 2075, and 964 EJ in 2100. This growth may be roughly approximated by a 1%/y growth rate. The avoided carbon emissions due to nuclear power are calculated on basis of 0.175 kg/kwh; the carbon contribution of non-nuclear primary energy is calculated on basis of 19 kg C per gigajoule, roughly the global average today.

Policy Implications and Conclusions

Nuclear power will be a significant contributor to the long-term global sustainable energy mix for years to come. Nuclear energy currently provides about 6% of primary energy worldwide and about one-sixth of global electricity. Although some countries, especially in the industrialized West, have plans to reduce their dependence on nuclear power, some expansion is expected in the developing world where electricity demand is expected to grow significantly in the coming decades.

However, for nuclear power to gain a broader constituency over the long term, it will have to overcome stiff commercial competition from other fuel sources and technologies. Advocates of nuclear power recently have focused on its potential role in reducing greenhouse gases. But as discussed, the savings in CO_2 emissions that can be offered by the nuclear power industry must be weighed against the intractable problem of nuclear waste disposal. For nuclear energy to face a viable future, technological innovation is needed that will address the serious challenges of waste management and proliferation risk.

A great number of the benefits that can be offered by new energy technologies, especially in environmental protection and providing diversity of supply and supply security, are public, rather than private, benefits. As the economics literature demonstrates, private firms are unlikely to provide such innovation at socially optimal prices. Thus, there is a strong argument for public-sector investment in improved energy technologies with significant environmental claims, such as small innovative reactors. The trick will be, however, how to implement such programs in a manner that doesn't encourage the government to pick winners without considerable study and testing.

The first step to healthy and viable innovation is to ensure government support for training in energy technologies including nuclear science and technology. In the U.S., for example, there has been a precipitous drop in the number of American students studying nuclear engineering, and some leading universities are on the threshold of irrevocably cutting out relevant essential educational programs and infrastructures. The U.S. Administration and relevant departments of government need to work with the university community to sustain nuclear science and technology education during the next decade in order to help preserve the nuclear power option. Similarly, Japan and other nations with a stake in nuclear energy must maintain R & D capabilities, and governments should promote support of long term research, development, demonstration, innovation in waste management and disposal, preparation of human and technical infrastructure and development of effective nuclear power regulations and restrictions that allow for a predictable and stable investment climate.

While national initiatives still hold promise, strategies must also reflect the growing trend toward internationalization of technological research. Linear and rigid development of nuclear power by single countries is becoming outdated, and the U.S., Japan and other nations should work together to shape a future nuclear fuel cycle that can garner shared support. The very large disconnect between American, European and Japanese fuel cycle policies is detrimental to sustaining nuclear power as a viable and potentially important option. All nations have an interest in shaping future technologies that satisfy non-proliferation concerns and energy security needs while minimizing waste and enhancing safety.

The U.S. and other industrialized nations have a strong interest in encouraging deployment of new energy technologies in the developing world to foster economic development and to minimize the environmental damage that will result from high rates of global economic growth. International institutions such as the World Bank and U.S. AID can be used to press projects that demonstrate sustainable energy, according to Neal Lane, Baker Institute Senior Fellow and former science advisor to President Clinton.

To avoid the wasteful allocation of public funds on technologies that might not be able to attain public acceptance, a stronger link is needed between the process of scientific design, evaluation, deployment and public policy. It is important that scientific and technical innovation not be developed in isolation but that ideas eventually be vetted in forums designed to promote dialogue on the goals and benefits of emerging technologies as well as on their costs and drawbacks. In this fashion, it will be more difficult for design R& D to become entrenched. Deployment can be improved as a broader range of stakeholders can influence the particulars of the development of new technologies, thereby improving the chances for social acceptance.

To propel commercial, environmentally friendly, proliferation resistance and socially acceptable designs, scientists benefit from meeting with and presenting their ideas not only to other scientists but also to well-informed representatives of public advocacy groups, industry representatives, public policy officials, academic public policy specialists, and diplomats.

In order to achieve this purpose, the U.S. and other allied governments should support universities and think tanks to convene workshops on emerging nuclear and other energy technologies, opening to public debate various aspects of emerging designs and future deployment planning. Competing designs should be compared in relation to their safety, environmental impact, proliferation resistance and potential social acceptance. By bringing public action groups and other specialized commentators in at the conceptual ground floor, scientists and public policy decision-makers can receive public feedback and promote education about new designs before expensive demonstration manufacturing begins. Workshop reports for programs that involve lay people can also provide improved information and transparency for non-scientist decision-makers who must regularly participate in discussions of government budget R & D allocations on an annual basis.

Resolution of disposition of current nuclear power plant spent fuel and high-level defense waste will be critical to preserving viable nuclear options for the U.S. This will require high-level administration attention. The Administration should work with states, nuclear utilities and other stakeholders to develop a path forward to resolve current disputes and developing a viable strategy for the federal government to meet its responsibilities for accepting spent fuel and disposing of high-level waste fuel. Minus a solution to this seemingly intractable issue, nuclear power will have difficulty attaining necessary social acceptance needed to site new facilities and remaining a commercially viable option for electricity generation.