Foundations for the fourth generation of nuclear power

Nuclear power shows great promise as an economical, safe, and emissions-free source for electrical energy as demand for electricity continues to grow.

BY JAMES A. LAKE

Plentiful, affordable electrical energy is a critically important commodity to nations wishing to grow their economy. Energy, and more specifically electricity, is the fuel of economic growth. More than one-third of the world's population (more than 2 billion people), however, live today without access to any electricity. Further, another 2 billion people in the world exist on less than 100 watts of electricity per capita. By comparison, the large economies of Japan and France use more than 800 watts of electricity per capita, and the United States uses nearly 1500 watts of electricity per capita.

As the governments of developing nations strive to improve their economies, and hence the standard of living of their people, electricity use is increasing. Several forecasts of electrical generation growth have concluded that world electricity demand will roughly double in the next 20–25 years, and possibly triple by 2050. This electrical generation growth will occur primarily in the rapidly developing and growing economies in Asia and Latin America.

This net growth is in addition to the need for replacement generating capacity in the United States and Europe as aging power plants (primarily fossil-fueled) are replaced. This very substantial worldwide electricity demand growth places the issue of where this new electricity generation capacity is to come from squarely in front of the developed countries. They have a fundamental desire (if not a moral obligation) to help these developing countries sustain their economic growth and improve their standard of living, while at the same time protecting the energy (and economic) security of their own countries.

There are currently 435 power reactors generating about 16 percent of the world's electricity. We know full well that nuclear power shows great promise as an economical, safe, and emissions-free source of electrical energy, but it also carries at least the perception of great problems, from public safety to dealing with radioactive wastes. I will have more to say about this later. For the moment, let me put forth the proposition that nuclear power should (and must) play a role in the future world energy supply, and perhaps should play an increasing role as the only technology capable of large-scale, near-term deployment without greenhouse gas emissions. If there is a moral imperative to assure the world of abundant, affordable, and clean electricity supplies, then there is no less of a moral imperative for us to assure that nuclear power is capable of taking its rightful place in this energy mix.

Changed nuclear paradigm

As we stand on the threshold of the new millennium facing unprecedented energy and economic growth around the world, we need to ask ourselves what state nuclear power is in, what challenges exist that may inhibit growth of nuclear power in the future, and what we need to be doing now to address these challenges.

The United States, as one of the pioneers in the development and application of nuclear power, serves as a very important indicator of the status of nuclear power, and of its future challenges. The 103 nuclear power plants in the United States generated 20 percent of the country's electricity (nearly 730 billion kWh) in 1999. Although much has been made of the fact that no new nuclear power plant orders have been placed in the United States since the early 1970s, the electricity generation from nuclear power has in fact risen 8 percent per year for the past 20 years. Plants placed on order in the 1970s have been completed (40 since 1980, the last of which was Watts Bar-1 in 1996), and the plant capacity factors have risen steadily to a high of 88 percent in 1999. The total electrical output from U.S. nuclear plants has thus risen from something less than 300 billion kWh in 1980 to 730 billion kWh today. This increased electrical generation capacity is one of the keys to the excellent economic performance of U.S. nuclear power.

At the same time that nuclear plant economic performance has improved, so too has safety performance. Safety performance indicators published by the World Association of Nuclear Operators (WANO) have shown consistent and steady improvement. These indicators include unplanned automatic shutdowns (where two-thirds of U.S. nuclear plants had zero in 1998), industrial safety (U.S. nuclear plants have an industrial accident rate less than one-tenth that of all U.S. industries), and collective radiation exposure to plant workers, which is currently 80 percent lower than 1980 values.

In the United States, and increasingly around the world, electricity markets are being deregulated in an effort to encourage competition and lower electricity prices for consumers. The early predictions of economic doom for nuclear-generated electricity in a competitive, deregulated U.S. market have been proven wrong.

The process leading to deregulation in 24 states has resulted in negotiated agreements related to recovery of the remaining capital costs of nuclear plants. Closure of the capital cost recovery issue has stimulated the financial interest in nuclear power because the remaining nuclear operating costs (operations, maintenance, and fuel) are very competitive with other electricity supplies in the U.S. In 1999, the average noncapital cost of nuclear-generated electricity was about 2 ¢/kWh. This is the low-price market leader in the U.S., approximately the same as coal and substantially lower than natural gas (at about 3.5 ¢/kWh and rising as both natural gas prices and gas turbine capital costs increase).

The improved economic environment for nuclear power in the United States has created a desire for acquisition of nuclear assets and a consolidation of ownership of nuclear power plants that is resulting in stronger, more efficient nuclear generating companies. The same consolidation is occurring in the world vendor market and in the nuclear fuel market. This market-driven consolidation, and the strong business interest in U.S. nuclear assets, is a positive indicator of the economic health of the U.S. nuclear industry.

The U.S. Nuclear Regulatory Commission is revising the way in which it regulates operations of nuclear power plants. The new regulatory process is performance-based and uses risk-prioritized regulatory criteria. The new process is believed to have the potential to remove undue regulatory (and hence economic) burden without compromising safety. NRC granted the first 20-year license extension to the Baltimore Gas & Electric Calvert Cliffs

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plant on March 23, 2000, and the Duke Oconee plant followed in May. The efficient processing of these license extension applications in less than two years has encouraged another eight plants to submit license extension applications, and nearly 30 more have announced plans to submit. The industry and NRC ultimately expect that 80 percent of the U.S. plants will apply for and receive license extensions.

Until very recently, the environmental benefits of clean nuclear energy have gone largely unrecognized and unappreciated. There is now an increasing international dialog about the environmental impacts of various energy sources in light of the growing body of scientific evidence related to health effects of particulate and gaseous emissions from the burning of fossil fuels, and the potential climate effects from rising CO_2 emissions. Environmental quality is becoming an increasingly important part of U.S. energy policy, and continued operation of existing nuclear plants, improvement in the capacity of these plants, and even construction of new nuclear power plants will be an important part of future U.S. plans if we are to balance our economic growth needs with our environmental stewardship responsibilities.

Challenges facing nuclear energy

The set of circumstances affecting the economic, regulatory, operations, safety, and environmental performance of nuclear power have changed rather dramatically in the United States in the past two or three years. There are signs of similar changes around the world. These changes allow us to have a relatively positive vision for the future of nuclear power, both for the continued operation of existing plants and for new construction. This vision, however, is based on finding successful solutions for five major challenges:

1. Nuclear power must remain economically competitive and must be capable of continuing to improve its economic performance in an increasingly deregulated world electricity market. Whereas the current *operating* economic parameters for existing nuclear plants are very good, the high capital cost ($1500–$2000/kW) and history of long construction, licensing, and commissioning times for new nuclear plants do not stand up to competition from natural gas in the U.S. market.
2. The public must remain confident in the safety of nuclear power plants and their fuel cycle. Although current light-water reactor technology is very safe, the heavy reliance on operations and maintenance presents a vulnerability to assuring continued safe operations, especially as the technology is deployed to countries with less sophisticated technical support infrastructures and different safety and work cultures.
3. Nuclear wastes must be managed and the back-end fuel cycle issues resolved. The ongoing political logjam in the efforts to close out the nuclear waste disposition issue in the United States, whether it involves opening a permanent or interim waste storage facility, can seemingly be resolved when we have the political will, leadership, and consensus to do so.
4. The proliferation potential of the commercial nuclear power fuel cycle must continue to be minimized. As nuclear power becomes more widely deployed worldwide, it is incumbent upon all of the nuclear supplier and operator nations to continually improve the proliferation resistance of the technology.
5. We must assure a sustainable manpower supply for the future and preserve the critical nuclear technology infrastructure around the world. International cooperation is necessary to help assure that a sustainable manpower supply is retained and that the critical technical infrastructure at R&D institutions, national laboratories, universities, and in industry, are preserved and utilized in an optimum fashion.

Responding to the challenges

Nuclear power originated from a first generation of light-water cooled plants in the 1950s and 60s. Those plants grew into the larger pressurized and boiling water reactors that are largely deployed around the world today. We are perhaps on the doorstep of the third generation of nuclear power technology that has evolved toward standardized and optimized light-water reactor plants with passive safety features. The world community is interested in finding even wider market acceptance for nuclear power in the future, and therefore we need to ask how well the technology can respond to the first four of the five challenges we outlined earlier. At the risk of oversimplifying a very complicated situation, I would offer that the major factor inhibiting expansion of nuclear power tomorrow is going to be cost.

Generation IV nuclear reactor technology will have to be very responsive to the challenges of reduced cost (especially capital cost), improved safety (especially the public perception of safety), minimization of wastes to minimize the long-term economic vulnerability to changes in waste disposition policies, and reduced potential for proliferation of nuclear materials. New (possibly revolutionary) reactor technology may be required to meet the capital cost requirements for the 21st century world market, and perhaps new approaches to "manufacturing" and rapidly deploying nuclear plants can play a pivotal role in reducing the capital cost of nuclear plants to future competitive levels. A fundamentally different way to attack the traditional economies of scale is to envision shifting nuclear plant construction from custom field construction toward more of a manufactured product composed of world components that are assembled or field-deployed, much as the manufacture of airplanes is different from the design and construction of airports. Such a concept of manufactured nuclear plants probably leads to looking more carefully at smaller-size (100-Mwe) plants, which, coincidentally, may find better market acceptance where capacity can be added incrementally to a system, more closely paralleling the demand.

Several advanced design concepts are already exploring the territory of smaller reactor plants, notably the South African Pebble bed modular reactor (PBMR) and the Argentinean CAREM reactor. Conceptual designs for several small-plant systems are also being evaluated under the U.S. Department of Energy's Nuclear Energy Research Initiative.

In May of this year, DOE sponsored a workshop attended by nearly 100 U.S. and international experts from the nuclear industry, academia, national laboratories, and international government and nongovernment organizations. The goal of the workshop was to develop a first-order set of world design goals that Generation IV nuclear power systems should meet in order to offer a viable and competitive future nuclear energy option for both developing and developed countries. The detailed results of this workshop can be found on <http://gen-iv.ne.doe.gov>. Briefly, the workshop concluded that:

- ■ The busbar cost of electricity from a Generation IV nuclear system must be competitive with other electricity generation sources in the region or country in which it is deployed (natural gas is the competitive benchmark in the United States, for example). This competitive cost is in the neighborhood of 3 ¢/kWh in the United States.
- ■ Generation IV systems must present the smallest possible risk to capital investment. Plant capital costs around $1000/kW and total construction times in the range of three to four years are highly desirable.
- ■ Generation IV plants must be capable of demonstrating improved safety margins, not only to regulatory authorities in the country in which they are deployed, but also to the public. As such, a very low likelihood of core damage may be necessary, but it is not sufficient. Generation IV designs may have to demonstrate, through integrated reactor testing that is open and transparent, that no severe core damage will result for plausible initiating accidents. This can be accomplished with core fuel and structural materials that do not melt at accident temperatures, coolant materials that are not reactive, and using passive cooling and heat removal systems that constrain core temperatures in a manageable range under the worst of accident conditions. There should be no credible accident scenario that would require offsite emergency response. Generation IV technology should be designed with today's experience and knowledge of operations and maintenance needs to be highly tolerant of human error.
- ■ The full life cycle—from mining to fuel fabrication to reactor operations to waste management, transportation, and plant decommissioning and decontamination—must be accounted for from the outset in a Generation IV system. In particular, complete solutions should be identified for all waste streams, and Generation IV technology should be designed to minimize the quantities of waste produced (for example, using very high-burnup fuels).
- ■ Generation IV advanced reactor systems, and their fuel cycle, should at a minimum preserve the status quo where material from the commercial nuclear fuel cycle is unattractive as a means of proliferation. Further, intrinsic features of the reactor system should improve the proliferation-resistant characteristics of the fuel cycle to disadvantage commercial nuclear

materials to the point where they are the least attractive path to the acquisition of nuclear weapons. Currently, within the DOE, methodologies are being developed to quantify and measure proliferation-resistance in order to guide and evaluate Generation IV candidates.

At the present time, the United States is not committed to a particular technical approach to, or reactor concept for, Generation IV. Rather, we are trying to assemble the broad resources of the U.S. and international R&D community at laboratories, universities, and research institutions, along with the world nuclear industry, to build consensus behind the critical performance requirements for 21st century world deployment, and to build a solid technical foundation for a long-term sustainable international design and development program.

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Among the assembled world nuclear experts are proponents of a wide variety of reactor concepts. Research teams around the world are already examining a wide variety of reactor concepts to compare their performance against the Generation IV requirements. These include high-temperature, gas-cooled reactors in pebble bed or prismatic configurations; liquid-metal-cooled reactor systems with conventional sodium or lead-alloy coolants; advanced water cooled systems, possibly employing supercritical steam; exotic systems, such as molten salts, that could function as waste burners; and others. Ultra-long-life reactor cores could raise the possibility of small reactors with cartridge cores that would not require refueling and could be field-deployed and removed at the end of life to be replaced by a new system.

In each of these cases, Generation IV reactor systems present technical challenges and barriers whose resolution, through focused R&D, can enable the needed system performance. For example, coated particle fuel performance at high temperature and high burnup is a key to the performance of the high-temperature, gas-cooled reactors. High-temperature materials performance, and particularly corrosion in lead-alloy-cooled systems, is an enabling technical issue. DOE intends to build a technology roadmap in 2001 for the leading Generation IV concept areas that will allow the U.S. R&D program to focus on the key enabling technical issues to support future selection by the market of candidate Generation IV systems for demonstration and deployment.

The path forward

Because the future nuclear energy market is a world market, Generation IV technology will be a world product. As such, the U.S. DOE's Office of Nuclear Energy, Science and Technology, under the leadership of William D. Magwood IV, is organizing a broad international dialog related to the requirements and attributes of the next generation of reactor technology. An international Generation IV Working Group consisting of senior government and technical personnel has begun to meet to discuss common goals and interests, and to establish bilateral and multilateral relationships and agreements that will allow the next generation of technology to be developed through joint R&D programs.

The ANS role

The American Nuclear Society, consistent with its mission and goals to be the recognized leaders in the advancement of nuclear science and technology and to be an active contributor to nuclear policy issues, is active in the planning and execution of the Generation IV strategy. ANS officers and members are key participants in U.S. DOE planning and international working groups and forums dealing with Generation IV.

ANS, as a respected professional society, can organize and facilitate technical forums for government, industry, the R&D and education community, and international leaders to discuss and debate the global issues important to nuclear energy and to support the formation of consensus and actions that foster a healthy future for the technology. ANS sponsors workshops, technical sessions, and topical meetings for the presentation of technical papers related to Generation IV and its technologies. ANS officers engage in regular meetings with senior officials from the U.S. government in Washington, D.C., in order to provide them with technical information with which to make sound policy decisions. Finally, the ANS Board of Directors passed a resolution in March of this year advocating the design, construction, and operation of a Generation IV nuclear power plant in the near term.

Implications for the future

The economic, operations, and safety performance of nuclear power in the United States and around the world is very good. This provides a solid foundation for us to envision a future for nuclear power that is very bright, so long as we can respond to the economic, safety, nuclear waste, proliferation-resistance, and infrastructure challenges. These are challenges worthy of our best efforts.