ENVIRONMENT

Next Generation Nuclear Power

New, safer and more economical nuclear reactors could not only satisfy many of our future energy needs but could combat global warming as well

By James A. Lake, Ralph G. Bennett, John F. Kotek on January 26, 2009

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Rising electricity prices and last summer's rolling blackouts in California have focused fresh attention on nuclear power's key role in keeping America's lights on. Today 103 nuclear plants crank out a fifth of the nation's total electrical output. And despite residual public misgivings over Three Mile Island and Chernobyl, the industry has learned its lessons and established a solid safety record during the past decade. Meanwhile the efficiency and reliability of nuclear plants have climbed to record levels. Now with the ongoing debate about reducing greenhouse gases to avoid the potential onset of global warming, more people are recognizing that nuclear reactors produce electricity without discharging into the air carbon dioxide or pollutants such as nitrogen oxides and smog-causing sulfur compounds. The world demand for energy is projected to rise by about 50 percent by 2030 and to nearly double by 2050. Clearly, the time seems right to reconsider the future of nuclear power.

No new nuclear plant has been ordered in the U.S. since 1978, nor has a plant been finished since 1995. Resumption of large-scale nuclear plant construction requires that challenging questions be addressed regarding the achievement of economic viability, improved operating safety, efficient waste management and resource utilization, as well as weapons nonproliferation, all of which are influenced by the design of the nuclear reactor system that is chosen.

Designers of new nuclear systems are adopting novel approaches in the attempt to attain success. First, they are embracing a system-wide view of the nuclear fuel cycle that encompasses all steps from the mining of ore through the management of wastes and the development of the infrastructure to support these steps. Second, they are evaluating systems in terms of their sustainability—meeting present needs without jeopardizing the ability of future generations to prosper. It is a strategy that helps to illuminate the relation between energy supplies and the needs of the environment and society. This emphasis on sustainability can lead to the development of nuclear energy–derived products besides electrical power, such as hydrogen fuel for transportation. It also promotes the exploration of alternative reactor designs and nuclear fuel–recycling processes that could yield significant reductions in waste while recovering more of the energy contained in uranium.

We believe that wide-scale deployment of nuclear power technology offers substantial advantages over other energy sources yet faces significant challenges regarding the best way to make it fit into the future.

Future Nuclear Systems In Response to the difficulties in achieving sustainability, a sufficiently high degree of safety and a competitive economic basis for nuclear power, the U.S. Department of Energy initiated the Generation IV program in 1999. Generation IV refers to the broad division of nuclear designs into four categories: early prototype reactors (Generation I), the large central station nuclear power plants of today (Generation II), the advanced lightwater reactors and other systems with inherent safety features that have been designed in recent years (Generation III), and the next-generation systems to be designed and built two decades from now (Generation IV) [see box on opposite page]. By 2000 international interest in the Generation IV project had resulted in a nine-country coalition that includes Argentina, Brazil, Canada, France, Japan, South Africa, South Korea, the U.K. and the U.S. Participating states are mapping out and collaborating on the research and development of future nuclear energy systems.

Although the Generation IV program is exploring a wide variety of new systems, a few examples serve to illustrate the broad approaches reactor designers are developing to meet their objectives. These next-generation systems are based on three general classes of reactors: gascooled, water-cooled and fast-spectrum.

Gas-Cooled Reactors Nuclear reactors using gas (usually helium or carbon dioxide) as a core coolant have been built and operated successfully but have achieved only limited use to date. An especially exciting prospect known as the pebble-bed modular reactor possesses many design features that go a good way toward meeting Generation IV goals. This gascooled system is being pursued by engineering teams in China, South Africa and the U.S. South Africa plans to build a full-size prototype and begin operation in 2006.

The pebble-bed reactor design is based on a fundamental fuel element, called a pebble, that is a billiard-ball-size graphite sphere containing about 15,000 uranium oxide particles with the diameter of poppy seeds. The evenly dispersed particles each have several high-density coatings on them. One of the layers, composed of tough silicon carbide ceramic, serves as a pressure vessel to retain the products of nuclear fission during reactor operation or accidental temperature excursions. About 330,000 of these spherical fuel pebbles are placed into a metal vessel surrounded by a shield of graphite blocks. In addition, as many as 100,000 unfueled graphite pebbles are loaded into the core to shape its power and temperature distribution by spacing out the hot fuel pebbles.

Heat-resistant refractory materials are used throughout the core to allow the pebble-bed system to operate much hotter than the 300 degree Celsius temperatures typically produced in today's light-water-cooled (Generation II) designs. The helium working fluid, exiting the core at 900 degrees C, is fed directly into a gas turbine/generator system that generates electricity at a comparatively high 40 percent thermal efficiency level, one quarter better than current lightwater reactors.

The comparatively small size and the general simplicity of pebble-bed reactor designs add to their economic feasibility. Each power module, producing 120 megawatts of electrical output, can be deployed in a unit one tenth the size of today's central station plants, which permits the development of more flexible, modest-scale projects that may offer more favorable economic results. For example, modular systems can be manufactured in the factory and then shipped to the construction site.

The pebble-bed system's relative simplicity compared with current designs is dramatic: these units have only about two dozen major plant subsystems, compared with about 200 in light-water reactors. Significantly, the operation of these plants can be extended into a temperature range that makes possible the low emissions production of hydrogen from water or other feedstocks for use in fuel cells and clean-burning transportation engines, technologies on which a sustainable hydrogen-based energy economy could be based.

These next-generation reactors incorporate several important safety features as well. Being a noble gas, the helium coolant will not react with other materials, even at high temperatures. Further, because the fuel elements and reactor core are made of refractory materials, they cannot melt and will degrade only at the extremely high temperatures encountered in accidents (more than 1,600 degrees C), a characteristic that affords a considerable margin of operating safety.

Yet other safety benefits accrue from the continuous, on-line fashion in which the core is refueled: during operation, one pebble is removed from the bottom of the core about once a minute as a replacement is placed on top. In this way, all the pebbles gradually move down through the core like gumballs in a dispensing machine, taking about six months to do so. This feature means that the system contains the optimum amount of fuel for operation, with little extra fissile reactivity. It eliminates an entire class of excess-reactivity accidents that can occur in current water-cooled reactors. Also, the steady movement of pebbles through regions of high and low power production means that each experiences less extreme operating conditions on average than do fixed fuel con-figurations, again adding to the unit's safety margin. After use, the spent pebbles must be placed in long-term storage repositories, the same way that used-up fuel rods are handled today.

Water-Cooled Reactors Even standard water-cooled nuclear reactor technology has a new look for the future. Aiming to overcome the possibility of accidents resulting from loss of coolant (which occurred at Three Mile Island) and to simplify the overall plant, a novel class of Generation IV systems has arisen in which all the primary components are contained in a single vessel. An American design in this class is the international reactor innovative and secure (IRIS) concept developed by Westinghouse Electric.

Housing the entire coolant system inside a damage-resistant pressure vessel means that the primary system cannot suffer a major loss of coolant even if one of its large pipes breaks. Because the pressure vessel will not allow fluids to escape, any resulting accident is limited to a much more moderate drop in pressure than could occur in previous designs.

To accomplish this compact configuration, several important simplifications are incorporated in these reactors. The subsystems within the vessel are stacked to enable passive heat transfer by natural circulation during accidents. In addition, the control rod drives are located in the vessel, eliminating the chance that they could be ejected from the core. These units can also be built as small power modules, thereby allowing more flexible and lower-cost deployment.

Designers of these reactors are also exploring the potential of operating plants at high temperature and pressure (more than 374 degrees C and 221 atmospheres), a condition known as the critical point of water, at which the distinction between liquid and vapor blurs. Beyond its critical point, water behaves as a continuous fluid with exceptional specific heat (thermal storage capacity) and superior heat transfer (thermal conductance) properties. It also does not boil as it heats up or flash to steam if it undergoes rapid depressurization. The primary advantage to operating above the critical point is that the system's thermal efficiency can reach as high as 45 percent and approach the elevated temperature regime at which hydrogen fuel production can become viable.

Although reactors based on supercritical water appear very similar to standard Generation II designs at first glance, the differences are many. For instance, the cores of the former are considerably smaller, which helps to economize on the pressure vessel and the surrounding plant. Next, the associated steam-cycle equipment is substantially simplified because it operates with a single-phase working fluid. In addition, the smaller core and the low coolant density reduce the volume of water that must be held within the containment vessel in the event of an accident. Because the low-density coolant does not moderate the energy of the neutrons, fast-spectrum reactor designs, with their associated sustainability benefits, can be contemplated. The chief downside to supercritical water systems is that the coolant becomes increasingly corrosive. This means that new materials and methods to control corrosion and erosion must be developed. Supercritical water reactor research is ongoing in Canada, France, Japan, South Korea and the U.S.

Fast-Spectrum Reactors A design approach for the longer term is the fast-spectrum (or high-energy neutron) reactor, another type of Generation IV system. An example of this class of reactor is being pursued by design teams in France, Japan, Russia, South Korea and elsewhere. The American fast-reactor development program was canceled in 1995, but U.S. interest might be revived under the Generation IV initiative.

Most nuclear reactors employ a thermal, or relatively low energy, neutron-emissions spectrum. In a thermal reactor the fast (high-energy) neutrons generated in the fission reaction are slowed down to "thermal" energy levels as they collide with the hydrogen in water or other light nuclides. Although these reactors are economical for generating electricity, they are not very effective in producing nuclear fuel (in breeder reactors) or recycling it.

Most fast-spectrum reactors built to date have used liquid sodium as the coolant. Future versions of this reactor class may utilize sodium, lead, a lead-bismuth alloy or inert gases such as helium or carbon dioxide. The higher-energy neutrons in a fast reactor can be used to make new fuel or to destroy long-lived wastes from thermal reactors and plutonium from dismantled weapons. By recycling the fuel from fast reactors, they can deliver much more energy from uranium while reducing the amount of waste that must be disposed of for the long term. These breeder-reactor designs are one of the keys to increasing the sustainability of future nuclear energy systems, especially if the use of nuclear energy is to grow significantly.

Beyond supporting the use of a fast-neutron spectrum, metal coolants have several attractive qualities. First, they possess exceptional heat-transfer properties, which allows metal-cooled reactors to withstand accidents like the ones that happened at Three Mile Island and Chernobyl. Second, some (but not all) liquid metals are considerably less corrosive to components than water is, thereby extending the operating life of reactor vessels and other critical subsystems. Third, these high-temperature systems can operate near atmospheric pressure, greatly simplifying system design and reducing potential industrial hazards in the plant.

More than a dozen sodium-cooled reactors have been operated around the world. This experience has called attention to two principal difficulties that must be overcome. Sodium reacts with water to generate high heat, a possible accident source. This characteristic has led sodium-cooled reactor designers to include a secondary sodium system to isolate the primary coolant in the reactor core from the water in the electricity- producing steam system. Some new designs focus on novel heat-exchanger technologies that guard against leaks.

The second challenge concerns economics. Because sodium-cooled reactors require two heat-transfer steps between the core and the turbine, capital costs are increased and thermal efficiencies are lower than those of the most advanced gas- and water-cooled concepts (about 38 percent in an advanced sodium-cooled reactor compared with 45 percent in a supercritical water reactor). Moreover, liquid metals are opaque, making inspection and maintenance of components more difficult.

Next-generation fast-spectrum reactor designs attempt to capitalize on the advantages of earlier configurations while addressing their shortcomings. The technology has advanced to the point at which it is possible to envision fast-spectrum reactors that engineers believe will pose little chance of a meltdown. Further, nonreactive coolants such as inert gases, lead or lead-bismuth alloys may eliminate the need for a secondary coolant system and improve the approach's economic viability.

Nuclear energy has arrived at a crucial stage in its development. The economic success of the current generation of plants in the U.S. has been based on improved management techniques and careful practices, leading to growing interest in the purchase of new plants. Novel reactor designs can dramatically improve the safety, sustainability and economics of nuclear energy systems in the long term, opening the way to their widespread deployment.

Nuclear Power Primer

Most of the world's nuclear power plants are pressurized water reactors. In these systems, water placed under high pressure (155 atmospheres) to suppress boiling serves as both the coolant and the working fluid. Initially developed in the U.S. based on experience gained from the American naval reactor program, the first commercial pressurized light-water reactor commenced operation in 1957.

The reactor core of a pressurized water reactor is made up of arrays of zirconium alloy–clad fuel rods composed of small cylinders (pellets) of mildly enriched uranium oxide with the diameter of a dime. A typical 17-by-17-square array of fuel rods constitutes a fuel assembly, and about 200 fuel assemblies are arranged to form a reactor core. Cores, which are typically approximately 3.5 meters in diameter and 3.5 meters high, are contained within steel pressure vessels that are 15 to 20 centimeters thick.

The nuclear fission reactions produce heat that is removed by circulating water. The coolant is pumped into the core at about 290 degrees Celsius and exits the core at about 325 degrees C. To control the power level, control rods are inserted into the fuel arrays. Control rods are made of materials that moderate the fission reaction by absorbing the slow (thermal) neutrons emitted during fission. They are raised out of or lowered into the core to control the rate of the nuclear reaction. To change the fuel or in the case of an accident, the rods are lowered all the way into the core to shut down the reaction.

In the primary reactor coolant loop, the hot water exits the reactor core and flows through a heat exchanger (called a steam generator), where it gives up its heat to a secondary steam loop that operates at a lower pressure level. The steam produced in the heat exchanger is then expanded through a steam turbine, which in turn spins a generator to produce electricity (typically 900 to 1,100 megawatts). The steam is then condensed and pumped back into the heat exchanger to complete the loop. Aside from the source of heat, nuclear power plants are generally similar to coal- or fuel-fired electrical generating facilities.

There are several variants of the light-water-cooled reactor, most notably boiling-water reactors, which operate at lower pressure (usually 70 atmospheres) and generate steam directly in the reactor core, thus eliminating the need for the intermediate heat exchanger. In a smaller number of nuclear power plants, the reactor coolant fluid is heavy water (containing the hydrogen isotope deuterium), carbon dioxide gas or a liquid metal such as sodium.

The reactor pressure vessel is commonly housed inside a concrete citadel that acts as a radiation shield. The citadel is in turn enclosed within a steel-reinforced concrete containment building. The containment building is designed to prevent leakage of radioactive gases or fluids in an accident.

The Case for Nuclear Power

Today 438 nuclear power plants generate about 16 percent of the world's electricity. In the U.S., 103 nuclear power plants provide about 20 percent of the country's electrical production. Although no new nuclear facilities have been ordered in the U.S. for more than two decades, the electrical output of U.S. generators has grown by almost 8 percent a year as the industry matured and became more efficient. In the past 10 years alone, American nuclear plants have added more than 23,000 megawatts—the equivalent of 23 large power plants—to the total electricity supply despite the lack of any new construction. In the meantime, the production increase has lowered the unit cost of nuclear power generation. This improvement has led to growing interest among the business community in extending plant operating licenses and perhaps purchasing new nuclear facilities.

It may be surprising to some that the use of nuclear energy has direct benefits to the environment, specifically air quality. Although debate continues about the potential for the disruption of the earth's climate by emissions of carbon dioxide and other greenhouse gases, there is no doubt about the serious health consequences of air pollution from the burning of fossil fuels. Unlike fossil-fuel power plants, nuclear plants do not produce carbon dioxide, sulfur or nitrogen oxides. Nuclear power production in the U.S. annually avoids the emission of more than 175 million tons of carbon that would have been released into the environment if the same amount of electricity had instead been generated by burning coal.

Little attention has been paid to nuclear energy's capacity for producing hydrogen for use in transportation fuel cells and other cleaner power plants. A very straightforward approach is to use the energy from a high-temperature nuclear reactor to drive a steam reforming reaction of methane. This process still creates carbon dioxide as a by-product, however. Several direct thermochemical reactions can give rise to hydrogen using water and high temperature. Research on the thermochemical decomposition of sulfuric acid and other hydrogen-forming reactions is under way in Japan and the U.S. The economics of nuclear-based hydrogen remain to be proved, but enormous potential exists for this route, perhaps operating in a new electricity-hydrogen cogeneration mode.

Improving Economics Any nuclear construction in the U.S. must address challenging economic issues concerning their capital costs and financing. The problem is that the current generation of nuclear power plants, represented by three Nuclear Regulatory Commission–certified advanced light-water reactor designs, costs about $1,500 per kilowatt electric (kWe) of generating capacity, which may not be sufficiently competitive to restart nuclear construction. A widely discussed cost goal for new (Generation III and IV) nuclear plant projects is $1,000 per kWe. Achievement of this aim would make them competitive (on a unit-cost basis) with the most economical alternative, the combined-cycle natural gas plant. Any next generation facilities must in addition be completed within about three years to keep financing costs to a manageable level. New streamlined, but as yet untried, licensing procedures should speed the process.

Given the past experience with nuclear projects in the U.S., it will be difficult for designers and builders to meet these goals. To achieve the cost objective, nuclear engineers are seeking to attain higher thermal efficiencies by raising operating temperatures and simplifying subsystems and components. Speeding plant construction will require the standardization of plant designs, factory fabrication and certification procedures; the division of plants into smaller modules that avoid the need for on-site construction; and the use of computerized assembly-management techniques. In this way, the building work can be verified in virtual reality before it proceeds in the field.

Advancing Safety As the economic performance of the nuclear power industry has improved over the past 20 years, so too has its safety performance. The Three Mile Island accident in 1979 focused the attention of plant owners and operators on the need to boost safety margins and performance. The number of so-called safety-significant events reported to the Nuclear Regulatory Commission, for example, averaged about two per plant per year in 1990 but had dropped to less than one tenth of that by 2000. In the meantime, public confidence in the safety of nuclear power has been largely restored since the Chernobyl accident in 1986, according to recent polls.

Long-term safety goals for next-generation nuclear facilities were formulated during the past year by international and domestic experts at the request of the U.S. Department of Energy. They established three major objectives: to improve the safety and reliability of plants, to lessen the possibility of significant damage during accidents, and to minimize the potential consequences of any accidents that do occur. Accomplishing these aims will require new plant designs that incorporate inherent safety features to prevent accidents and to keep accidents from deteriorating into more severe situations that could release radioactivity into the environment.

Nuclear Waste Disposal and Reuse Outstanding issues regarding the handling and disposal of nuclear waste and safeguarding against nuclear proliferation must also be addressed. The Yucca Mountain long-term underground repository in Nevada is being evaluated to decide whether it can successfully accept spent commercial fuel. It is, however, a decade behind schedule and even when completed will not accommodate the quantities of waste projected for the future.

The current "once-through," or open, nuclear fuel cycle uses freshly mined uranium, burns it a single time in a reactor and then discharges it as waste. This approach results in only about 1 percent of the energy content of the uranium being converted to electricity. It also produces large volumes of spent nuclear fuel that must be disposed of in a safe fashion. Both these drawbacks can be avoided by recycling the spent fuel—that is, recovering the useful materials from it.

Most other countries with large nuclear power programs—including France, Japan and the U.K.—employ what is called a closed nuclear fuel cycle. In these countries, used fuel is recycled to recover uranium and plutonium (produced during irradiation in reactors) and reprocess it into new fuel. This effort doubles the amount of energy recovered from the fuel and removes most of the long-lived radioactive elements from the waste that must be permanently stored. It should be noted, though, that recycled fuel is today more expensive than newly mined fuel. Current recycling technology also leads to the separation of plutonium, which could potentially be diverted into weapons.

Essentially all nuclear fuel recycling is performed using a process known as PUREX (plutonium uranium extraction), which was initially developed for extracting pure plutonium for nuclear weapons. In PUREX recycling, used fuel assemblies are transported to a recycling plant in heavily shielded, damage-resistant shipping casks. The fuel assemblies are chopped up and dissolved by strong acids. The fuel solution then undergoes a solvent-extraction procedure to separate the fission products and other elements from the uranium and the plutonium, which are purified. The uranium and plutonium are used to fabricate mixed oxide fuel for use in light-water reactors.

Recycling helps to minimize the production of nuclear waste. To reduce the demand for storage space, a sustainable nuclear fuel cycle would separate the short-lived, high-heat-producing fission products, particularly cesium 137 and strontium 90. These elements would be held separately in convectively cooled facilities for 300 to 500 years, until they had decayed to safe levels. An optimized closed (fast-reactor) fuel cycle would recycle not just the uranium and plutonium but all actinides in the fuel, including neptunium, americium and curium. In a once-through fuel cycle, more than 98 percent of the expected long-term radiotoxicity is caused by the resulting neptunium 237 and plutonium 242 (with half-lives of 2.14 million and 387,000 years, respectively). Controlling the long-term effects of a repository becomes simpler if these long-lived actinides are also separated from the waste and recycled. The removal of cesium, strontium and the actinides from the waste shipped to a geological repository could increase its capacity by a factor of 50.

Because of continuing interest in advancing the sustainability and economics of nuclear fuel cycles, several countries are developing more effective recycling technologies. Today an electrometallurgical process that precludes the separation of pure plutonium is under development in the U.S. at Argonne National Laboratory. Advanced aqueous recycling procedures that offer similar advantages are being studied in France, Japan and elsewhere.

Ensuring Nonproliferation A critical aspect of new nuclear energy systems is ensuring that they do not allow weapons-usable materials to be diverted from the reprocessing cycle. When nations acquire nuclear weapons, they usually develop dedicated facilities to produce fissile materials rather than collecting nuclear materials from civilian power plants. Commercial nuclear fuel cycles are generally the most costly and difficult route for production of weapons-grade materials. New fuel cycles must continue to be designed to guard against proliferation. *—J.A.L., R.G.B. and J.F.K.*

How Secure are Nuclear Plants from Terrorists?

The tragic events of September 11, 2001, raise troubling questions about the vulnerability of nuclear facilities to terrorist attacks. Although stringent civilian and military security countermeasures have been implemented to stop determined assaults, the deliberate crash of a large commercial airliner looms in the imagination. So, should Americans be worried? The answer is no and yes.

A nuclear power plant is not an easy target for an airliner flying at high speed, because an off-center hit on a domed, cylindrical containment building would not substantially affect the building structure. Located at or below grade, the reactor core itself is typically less than 10 feet in diameter and 12 feet high. It is enclosed in a heavy steel vessel surrounded by a concrete citadel. Reactor containment designs differ in their details, but in all cases they are meant to survive the worst of nature's forces (including earthquakes, tornadoes and hurricanes). Despite not being designed to resist acts of war, containment enclosures can withstand crashes of small aircraft.

Even though the reactor core is protected, some of the piping and reactor cooling equipment, the auxiliary apparatus and the adjacent switchyard may be vulnerable to a direct hit. Nuclear power stations, however, are outfitted with multiple emergency cooling systems, as well as with emergency power supplies, should power be disabled. In the improbable event that all of these backup precautions were destroyed, the reactor core could overheat and melt. But even in this extreme case, which is similar to what occurred at Three Mile Island, the radioactive core materials would still be contained within the pressure vessel.

If nuclear plants have an Achilles' heel, it is the on-site temporary storage facilities for spent nuclear fuel. Although these depositories usually contain several used fuel assemblies and therefore more total radioactivity than a reactor does, most of the more dangerous radioactive isotopes in the old fuel have already decayed away. This is particularly true for the gaseous fission products that could get into the air, whose half-lives can be measured in months. Spent fuel assemblies that have been removed relatively recently from reactors are kept in deep pools of water to cool them and shield the radiation they emit. These open-air pools are surrounded by thick-walled, steel-lined concrete containers. After a few years, the materials are transferred into concrete, air-cooled dry fuel-storage casks.

Although cooling pools provide a relatively small and, hence, difficult target for terrorists, a pinpoint attack could drain a pool's water, causing the fuel to overheat and melt. Experts say that a standard fire hose would be enough refill the pool. Even if the fuel were to melt, little radioactive particulate would be produced that might become airborne, specialists say. An airliner crash into dry fuel-storage casks would probably just knock them aside. If any casks cracked, broken bits of oxidized fuel cladding could carry some radioactivity skyward, according to nuclear safety experts.

Some experts believe that the Nuclear Regulatory Commission will soon order the reinforcement of auxiliary nuclear plant equipment and waste storage facilities.

Should such a terrorist onslaught occur, plans are in place to evacuate nearby residents, although it must be said that critics claim these schemes to be impractical. It is thought, however, that there would be about eight to 10 hours available to get out safely, long before evacuees received a significant radioactive dose. The most severe potential adverse effect could be long-term contamination of the local area by airborne particulates, which would be expensive to clean up. —*The Editors*

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