Generation IV Nuclear Energy Systems
February 24, 2000

I. DOE Motivations

After having terminated the Advanced Light Water Reactor program in 1998, the Clinton Administration initiated a reformed though limited program of nuclear energy research for 1999 and beyond. Spurred on by recommendations of President Clinton's Committee of Advisors on Science and Technology (PCAST), the U.S. Department of Energy -- led by Under Secretary Ernest Moniz, the former chairman of the Physics Department at the Massachusetts Institute of Technology -- launched the Nuclear Energy Research Initiative (NERI) and won funding from the Republican-controlled Congress at a level of $19 million for its first year of existence. PCAST had advised that the potential benefits of nuclear energy in addressing carbon dioxide emissions justified a modest research initiative -- they recommended starting at about $40 million per year and increasing to $120 million in 2003 -- to overcome four potential barriers to the expanded use of nuclear energy: economics, safety, waste management and proliferation.

Under Secretary Ernest Moniz

The Administration has not gone so far as to advocate building more nuclear power plants in the United States. Furthermore, to keep things in perspective, it should be recognized that DOE's requested funding for NERI has not only been far shy of PCAST's recommended level but also only a small fraction of its current funding for energy efficiency and renewable energy programs, which received $362 million in FY2000, or nuclear fusion, which received $250 million. Nonetheless, in a March 1999 interview with Numark Associates for the *Nuclear Top Ten, 1999* report, Secretary of Energy Bill Richardson stated that the nation's existing nuclear plants "are essential" to meeting future power demand as well as international carbon goals, and that the Administration is committed to "maintaining nuclear energy as a viable option for the long term." DOE estimates that:

> to meet the projected growth in world energy demand while stabilizing atmospheric concentrations of carbon dioxide at twice the current level... the percent of energy from sources that do not emit carbon must grow... at an average rate of 4 to 5.5 percent per year. Only five energy sources appear capable of providing a substantial fraction of the required carbon-free supply in 2050: nuclear fission, solar, 'decarbonized' fossil fuels, and, to a lesser extent, biomass and wind.[1]

[1] U.S. Department of Energy, Office of Nuclear Energy, Science and Technology, "Generation IV: Looking to the Future of Nuclear Power," available at http://www.anlw.anl.gov/gen4/, citing *Climate Change and the Future of Nuclear Energy*, Dr. Steve Fetter, University of Maryland, December 1998, paper prepared for Pugwash Meeting 243, "The Prospects of Nuclear Energy," Paris, December 4-5, 1998.

DOE adds that each of these power sources faces challenges before they can be significantly expanded, so broad-based energy R&D is needed to ensure that acceptable substitutes to carbon-emitting fuels will be available worldwide when needed. Specifically in the nuclear area, **DOE's Office of Nuclear Energy, Science and Technology (DOE-NE) has offered the following comments on the R&D challenges in the areas called out by PCAST, which form the underlying basis for NERI:**

- Safety and Waste Management: DOE notes that nuclear energy has a reputation as a dangerous and polluting technology. They consider the point debatable, but state that there is no question that it needs to be addressed if nuclear is to play a significant future role.

- Economics: DOE points to substantial improvements in the performance of U.S. nuclear power plants as well as the further expected improvements resulting from industry consolidation, but notes that the Three Mile Island accident "made clear to the financial community the vulnerability of existing nuclear plants to "fiscally catastrophic failure." Furthermore, DOE suggests that advanced LWRs "have been designed to meet the requirements of regulated U.S. utilities that were guaranteed reimbursement of all allowable costs," and that "with the change toward deregulation in U.S. electricity generation, [these] designs are insufficiently cost-competitive. To be competitive, and in the absence of carbon taxes or other policy changes that increase the cost of fossil fueled electrical generation, the life-cycle cost will have to be brought to around 3.0 cents per kWh [from an estimated 4.5 cents per kWh for ALWRs] and capital costs will have to be brought under $700 a kilowatt [from an estimated $1500 to $1800 per kW for ALWRs]."

- Proliferation: DOE considers present-day safeguards to be adequate but notes the potential benefits if an even higher degree of resistance to proliferation can be introduced, such as new technologies that could decrease the cost of providing safeguards.

NE Director Bill Magwood

As a product of NERI, the notion of "Generation IV" reactors was first raised by DOE-NE Director Bill Magwood at the American Nuclear Society's summer meeting in Boston, Massachusetts in June 1999. Magwood defines the four generations of nuclear reactors as follows:

- Generation I: Early, small, Atoms-for-Peace era plants (mostly now shut down, e.g. Shippingport, Dresden, Fermi-1 and Magnox reactors)
- Generation II: The vast majority of nuclear plants now in operation (LWR, CANDU, HTGR/AGR, VVER/RBMK)

- Generation III: Advanced evolutionary LWRs, e.g. the ABWR, the System 80+, the AP600 and the European Power Reactor
- Generation IV: "Technologies that make further advances in both proliferation resistance and safety performance, while providing a nuclear option that is economically competitive with natural gas."

II. Criteria for Generation IV Reactors

DOE has been careful not to identify specific reactor designs that it considers compatible with Generation IV principles. One DOE insider suggested to Numark Associates that DOE prefers to focus on criteria at this stage, rather than specific concepts which might lead various reactor proponents to begin "lobbing grenades" at each other. DOE is focusing on the principles, such as making reactors that are easy to build, proliferation resistant, passively safe, etc. Eventually, within one to two years, it is expected that DOE will proceed through a "Technology Roadmap" exercise in which they will call upon various reactor designers, determine the state of each technology and identify any "showstoppers."

DOE-NE has identified several possible characteristics for Generation IV reactors such as:

- Modular reactors that are manufactured rather than constructed, built "more like aircraft than airports."
- Simplified designs with fewer major components and rapid construction, in response to utilities who want to be able to build them in two to three years.
- Higher coolant temperatures allowing higher efficiencies.
- Proliferation-resistant designs, or "intrinsic safeguards," e.g. reactor systems that contain all of their fuel for long periods of operation without needing, or even without being able, to reshuffle or refuel. Ultra-long-lived, high burnup cores would also reduce the volume of high-level waste generated.
- Minimized waste generation, including designs that would produce substantially less low-level waste.

DOE's Nuclear Energy Research Advisory Committee has emphasized the need to bring down capital costs as well as reduce investment risk by abating concerns over safety, waste management and non-proliferation. NERAC has noted that Generation IV could well be a non-LWR technology and has described Generation IV as an opportunity for "a new, fresh approach."

Despite DOE's care to avoid naming any specific reactor designs, it is widely presumed in the United States that candidate Generation IV technologies will likely include various innovative LWR concepts; high-temperature gas-cooled reactor designs; metal cooled reactors (lead, lead-bismuth, sodium, etc.); molten salt-cooled reactors; thorium-based designs; etc.

III. U.S. Activities to Develop Generation IV

While it has initiated funding under NERI for a few reactor projects that could be considered Generation IV reactors, DOE has also begun a dialogue within the U.S. and with foreign governments on the Generation IV concepts. Regarding the projects, **DOE awarded the first round of NERI funding (about $19 million) to a total of 46 projects in May 1999, approximately one-third of which address new reactor designs or component designs.** Examples include:

- A University of New Mexico collaboration with Westinghouse to assess the feasibility of developing an integrated reactor and energy conversion system designed for the developing countries market. The design involves a core with a lifetime exceeding 15 years without fuel shuffling or refueling, such that the entire core could be removed and shipped back to the country of origin at the end of its life.

- A Westinghouse collaboration with several universities to develop a Secure Transportable Autonomous Light Water Reactor (STAR-LW), also targeted at developing countries. STAR-LW would have a core lifetime on the order of 15 years; a high degree of inherent safety; and reduced capital costs due to the elimination of entire systems such as refueling and most vessel penetrations. An alternate STAR design also being funded under NERI would transfer heat from the primary coolant to the secondary coolant through the reactor vessel wall. As it would completely eliminate through-vessel connections, the reactor could remain sealed throughout its lifetime and is referred to as an Encapsulated Nuclear Heat Source or as a "nuclear battery."

- A Brookhaven National Laboratory collaboration with Purdue University and Hitachi to develop a High Conversion BWR fueled with fissile plutonium and fertile thorium oxide. The design involves a very tight lattice and would operate with a fast neutron spectrum. It aims to consume plutonium inventories, achieve very high burnup and reduce operating costs.

- A Sandia National Laboratories collaboration with universities, another laboratory and General Atomics to develop a Direct Energy Conversion Fission Reactor that would capture the energy of fission fragments with no intermediate conversion to thermal energy, allowing a maximum efficiency of over 80%.

- A Purdue University collaboration with Brookhaven National Laboratory to design simplified BWRs in compact 200 MWe modules and as a full-size 1200 MWe reactor. The designs would have passive safety systems.

- A General Atomics-led project to define a way to use thermochemical watersplitting to produce hydrogen fuels using an advanced high temperature reactor.

- An INEEL collaboration with Bechtel and Oregon State University to develop a small, natural circulation PWR with flexible applications either for electric power generation or process heat, and deployable in a variety of locations.

- An Argonne National Laboratory collaboration with the French Commissariat à l'Énergie Atomique to study the neutronic characteristics of a lead-cooled fast reactor system.

The U.S. Congress only approved a slight increase in NERI funding for FY 2000, at $22.5 million. Only about $3 million of this is available for new Round 2 projects, since the first round awards went to multi-year projects that depend on these continuing appropriations. Nonetheless, DOE issued a solicitation for proposals to receive this $3 million, which specifically identifies Generation IV systems as one of the program elements (the other two being Improved Proliferation Resistance of Reactor Systems and Fuel Cycles, and Fundamental Science), describing it as:

> ... the investigation and preliminary development of Generation IV reactor and power conversion system concepts that offer the prospect of improved performance and operation, design simplification, enhanced safety or reduced overall cost. Proposed projects may involve innovative reactor, systems or components designs, alternative power conversion cycles, advanced instrumentation and control, and other important design features and characteristics... These designs may be compact or modular designs suitable for transport to remote locations. Desirable features might include long-lived reactor cores that minimize, or avoid altogether, the need for refueling.
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> ... This program element also will include projects intended to identify and evaluate alternative methods and technologies to reduce the costs of constructing future nuclear power plants [such as] modularization and/or prefabrication [and] increased automation and use of robots in the manufacture of equipment and in plant construction.[2]

Round 2 proposals were due to DOE on February 17, 2000.

Furthermore, **DOE's budget request for FY 2001 was just sent to Congress in early February. The request includes a proposed large increase in NERI, to $35 million,** including $6.8 million for a new International Clean Energy Initiative/International NERI, "to

[2] U.S. Department of Energy, Office of Nuclear Energy, Science and Technology, "Financial Assistance Solicitation No. DE-PS03-00SF22016: Nuclear Energy Research Initiative," available at http://www.oak.doe.gov/financial/sf22016.pdf.

promote foreign collaborative research focused on advanced technologies for improving the cost, safety, waste management, and proliferation resistance of advanced nuclear energy systems."

Besides project funding, DOE's dialogue on Generation IV has received substantial attention. At a closed workshop held one month ago, DOE officials met with a small group of counterparts from the governments of Argentina, Brazil, Canada, France, Japan, South Africa, South Korea and the United Kingdom (other countries had been invited but declined to participate). Two discussion points reportedly received the most attention:

- Generation IV vs. Generation III: This was reportedly a sensitive issue. Countries that are not building Generation III reactors, including the United States, feel that there are problems with Generation III reactors (especially economics) and prefer to go beyond Generation III directly to accelerated Generation IV R&D. In contrast, Japan, South Korea and others emphasized the importance of Generation III reactors as a transition phase to Generation IV.

- Importance of Proliferation Resistance: There was reportedly a mixture of viewpoints on how important it is for Generation IV reactors to have greater proliferation resistance than Generation II or III reactors, and how important a criterion this is for Generation IV reactors in contrast with improving the economic, safety and waste characteristics. The divergence of views seems to reflect different perceptions of whether Generation IV reactors are intended to be built in developing countries. One participant suggested that the international community's main message to DOE was that the priorities for Generation IV are "economics, economics and economics." Still, DOE likely believes there is a common international objective that future reactor systems should have increased proliferation resistance.

Delegates to the workshop issued a joint communiqué expressing a "consensus view" that, among other things:

- Nuclear power continues to hold important electricity supply and clean air benefits for the future;
- Third-generation nuclear technology will continue to provide a viable option in some countries for the next two decades, although its competitiveness must be improved;
- Future nuclear power technology development should take into account enhancements in economics, safety, energy supply security, waste management and nonproliferation, and such technology must be equally accessible to both industrialized and industrializing nations; and
- Generation IV systems should address these issues in a manner that promotes greater public acceptance and cost competitiveness.

The communiqué concluded that Generation IV systems should be investigated on a multilateral basis as an option for the future.

DOE now plans a second workshop focusing on Generation IV technologies in early May in Washington, D.C. The meeting, which will also be closed to the public, is expected to include government officials as well as vendor and utility representatives, the financial community and others. The meeting is to focus on the criteria for future Generation IV reactors.

IV. U.S. Reactions to Generation IV Program

Reactions within the United States nuclear energy community to DOE's Generation IV program have been generally positive. The Nuclear Energy Institute is planning a Nuclear Energy R&D Summit in Washington on March 2, reflecting the nuclear industry's interest in extending the nuclear future beyond the current generation of reactors. In recent comments on DOE's proposed NERI funding increase for FY2001, NEI stated that "We applaud the significant boost in funding for NERI. The program is essential if nuclear energy is to continue to meet 20 percent of the nation's electricity needs, cleanly and reliably."

The American Nuclear Society has been supportive of Generation IV, their main complaint being that DOE's nuclear program budgets continue to be "miserly," as suggested in recent ANS comments on DOE's FY2001 budget request. ANS notes that NERI is the only DOE nuclear program that is really growing. American Nuclear Society President Andy Kadak dedicated a Special Session to Generation IV reactors at ANS's November 1999 winter meeting, with presentations by Magwood; director of strategic programs at the utility PECO Nuclear, Ward Sproat; ABB-Combustion Engineering's George Davis; South African utility Eskom's David Nichols, speaking on Eskom's Pebble Bed Modular Reactor; former executive of GE Nuclear, Bert Wolfe; and MIT professor Mujid Kazimi.

Comments of particular interest at the November session included Sproat's, who outlined what he views as the requirements future reactors will have to meet before utilities will buy them: a generation cost under 3 cents/kWh; capacity factors greater than 85%; 24-month refueling cycles; load following capability; 60-year operating life; on-line maintenance capabilities; inherent safety features; high integrity fuel; and well-developed probabilistic risk assessments showing significant risk reduction from currently-operating plants. Wolfe commented that a very large amount of money and effort has already gone into LWR technology and that DOE should be very careful before abandoning that in favor of a new generation of reactors.

No comments by anti-nuclear groups concerning the Generation IV program have been identified, but it should be noted that many of these groups have fundamentally rejected any use of nuclear power technology, regardless of possible improvements such as the Generation IV program proposes to achieve.

V. Prospects

In closing, the U.S. DOE is making a strong push for development of a new generation of reactors but has little money to do so and has begun a dialogue process to boost the idea, with generally positive reactions. With virtually no U.S. utility interest in Generation III technology unless capital costs can be substantially reduced, and with interest in developing a diversity of non-carbon emitting technologies appropriate for developing countries, DOE's motivations are understandable.

Senator Pete Domenici

The prospects are harder to assess as they depend heavily on how the private sector handles Generation IV in the coming years. Congress will likely support modest year-to-year increases in NERI funding, under the leadership of the powerful Senate Energy Appropriations Chairman and nuclear energy champion Pete Domenici, but fission-related research can be expected to remain a small fraction of U.S. budgets for fusion, renewable energy and energy efficiency for the foreseeable future. Despite the booming U.S. economy and an upward surge in tax revenues collected, Congressional appropriations continue to be constrained by balanced-budget spending caps agreed to in 1997, and Members on both sides of the aisle generally oppose broad government-sponsored research on already well-established fission energy. The Clinton Administration may have coined the term "Generation IV" and is clearly trying to establish the launch pad, but the government is unlikely to be the one to put this program into orbit.