THE JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY OF RICE UNIVERSITY

NEW ENERGY TECHNOLOGIES:

A POLICY FRAMEWORK FOR MICRO-NUCLEAR TECHNOLOGY

1. NUCLEAR POWER, SMALL NUCLEAR TECHNOLOGY, AND THE ROLE OF TECHNICAL INNOVATION: AN ASSESSMENT
ROBERT N. SCHOCK, CENTER FOR GLOBAL SECURITY RESEARCH, *LAWRENCE LIVERMORE NATIONAL LABORATORY*,
NEIL W. BROWN, ENERGY AND ENVIRONMENT PROGRAM, *LAWRENCE LIVERMORE NATIONAL LABORATORY* AND
CRAIG F. SMITH, ENERGY AND ENVIRONMENT PROGRAM, *LAWRENCE LIVERMORE NATIONAL LABORATORY*

2. SMALL INNOVATIVE REACTOR DESIGNS –USEFUL ATTRIBUTES AND STATUS OF TECHNOLOGY
EHUD GREENSPAN, DEPARTMENT OF NUCLEAR ENGINEERING, *UNIVERSITY OF CALIFORNIA AT BERKELEY* AND
NEIL W. BROWN, FISSION ENERGY AND SYSTEMS SAFETY PROGRAM, *LAWRENCE LIVERMORE NATIONAL LABORATORY*

3. ECONOMIC AND MARKET POTENTIAL OF SMALL INNOVATIVE REACTORS
JOHN J. TAYLOR, VICE PRESIDENT, NUCLEAR POWER (RETIRED), *ELECTRIC POWER RESEARCH INSTITUTE*

4. COMMENTS ON THE DEVELOPMENT PATH NEEDED FOR PROLIFERATION-RESISTANT NUCLEAR POWER
H.A. FEIVESON, SENIOR RESEARCH POLICY SCIENTIST, PROGRAM ON SCIENCE AND GLOBAL SECURITY,
PRINCETON UNIVERSITY

5. ON SOCIAL ACCEPTANCE OF NUCLEAR POWER
MICHAEL W. GOLAY, PROFESSOR OF NUCLEAR ENGINEERING, *MASSACHUSETTS INSTITUTE OF TECHNOLOGY*

6. DEVELOPMENT STRATEGY FOR SMALL INNOVATIVE REACTORS (SIR) AND ENERGY SECURITY
TATSUJIRO SUZUKI, CHIEF SENIOR RESEARCHER, *CENTRAL RESEARCH INSTITUTE OF ELECTRICAL POWER INDUSTRY (CRIEPI), JAPAN*

7. TRENDS IN THE DEVELOPMENT OF MODULAR, HIGH-TEMPERATURE, GAS-COOLED, NUCLEAR REACTORS FOR COMMERCIAL USE AND THEIR SIGNIFICANCE
YASUO TSUCHIE, SENIOR CHIEF RESEARCHER, ADVANCED REACTOR & TECHNOLOGY RESEARCH AND DEVELOPMENT DEPARTMENT,
JAPAN ATOMIC POWER COMPANY

PREPARED IN CONJUNCTION WITH AN ENERGY STUDY SPONSORED BY
THE CENTER FOR INTERNATIONAL POLITICAL ECONOMY
AND
THE JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY
RICE UNIVERSITY – AUGUST 2001

THE JAMES A. BAKER III
INSTITUTE FOR PUBLIC POLICY
OF
RICE UNIVERSITY

NEW ENERGY TECHNOLOGIES:

A POLICY FRAMEWORK FOR MICRO-NUCLEAR TECHNOLOGY

NUCLEAR POWER, SMALL NUCLEAR TECHNOLOGY, AND THE ROLE OF TECHNICAL INNOVATION: AN ASSESSMENT

ROBERT N. SCHOCK
CENTER FOR GLOBAL SECURITY RESEARCH
LAWRENCE LIVERMORE NATIONAL LABORATORY

NEIL W. BROWN
ENERGY AND ENVIRONMENT PROGRAM
LAWRENCE LIVERMORE NATIONAL LABORATORY

CRAIG F. SMITH
ENERGY AND ENVIRONMENT PROGRAM
LAWRENCE LIVERMORE NATIONAL LABORATORY

PREPARED IN CONJUNCTION WITH AN ENERGY STUDY SPONSORED BY
THE CENTER FOR INTERNATIONAL POLITICAL ECONOMY
AND
THE JAMES A. BAKER III INSTITUTE FOR PUBLIC POLICY
RICE UNIVERSITY – AUGUST 2001

Abstract*

An overview of energy-system projections into the new century leads to the conclusion that nuclear power will play a significant role. How significant a role will be determined by the marketplace. Within the range of nuclear-power technologies available, small nuclear-power plants of innovative design appear to fit the needs of a number of developing nations and states. These plants have the potential advantage of modularity, are proliferation-resistant, incorporate passive safety features, minimize waste, and could be cost-competitive with fossil-fuel plants.

Introduction

Our task is to give an overview of the technology for small, innovative nuclear systems and an assessment of the conditions that may influence the future viability of these systems. To do this, we must first understand such complicated subjects as future global energy scenarios, the commercial marketplaces likely to exist for any new technology to compete in, as well as the technologies themselves and their attributes—not only of small reactor systems, but also of the technologies against which they must compete, including large nuclear systems. We cannot give answers to the many questions that would arise from such study, but rather try and set the framework within which work to follow should provide the necessary detail.

As we enter the new millennium, the world is subject to a confluence of forces that offer unique opportunities: the transition to a knowledge-based society, the emergence of a truly global economy, and the pursuit by society of sustainable systems with minimal environmental impacts. These forces are likely to converge to enable major improvements in the wealth-creating capacity and well-being of the world's inhabitants. The developed nations are leading in bringing these improvements to world markets. Our own economy, society, political well-being, and even our security will benefit from these improvements.

No single system is more important to this dynamic than energy, which powers the economy, provides the engine to increase the quality of life of all the globe's inhabitants, but at the same time is also the most responsible for environmental pollution of the atmosphere and oceans. We in the developed world are in

* This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

a position of leadership in introducing modern energy systems that are increasing worldwide standards of living and providing industry with safe and reliable energy to drive both the information technology revolution and the global economy.

The Global Energy Future

What the energy systems of the future will be is not known, but we do know that their mix and distribution will be determined by society's priorities, as expressed in the marketplace. Current extrapolations and scenarios of global energy growth rates vary, but significantly, they center on 25 to 50% growth over the next 20 years and 250% growth over the next 50 years. It is interesting that a large number of recent scenarios done for the Intergovernmental Panel on Climate Change (IPCC) [1], as part of their most recent assessment of emission-mitigation strategies to stabilize carbon dioxide in the atmosphere, show even larger increases of up to 350% or three and one-half times existing energy-use levels. More importantly, the growth rates in electric power are even higher. A recent projection by the Electric Power Research Institute has a 500% increase in electric power by 2050 [2].

Where will all of this energy come from? Again we do not know, but the IPCC scenarios are instructive. They are consistent with the opinions of leaders from around the world, many if not most, with a strong leaning toward environmental concerns. **Figure 1** shows technologies, with projections of the range of their contributions to global electricity production in 2050 from 30 scenarios, chosen for different stabilization levels of carbon dioxide in the atmosphere and different economic assumptions. The median value of each technology over all scenarios is shown by a square.

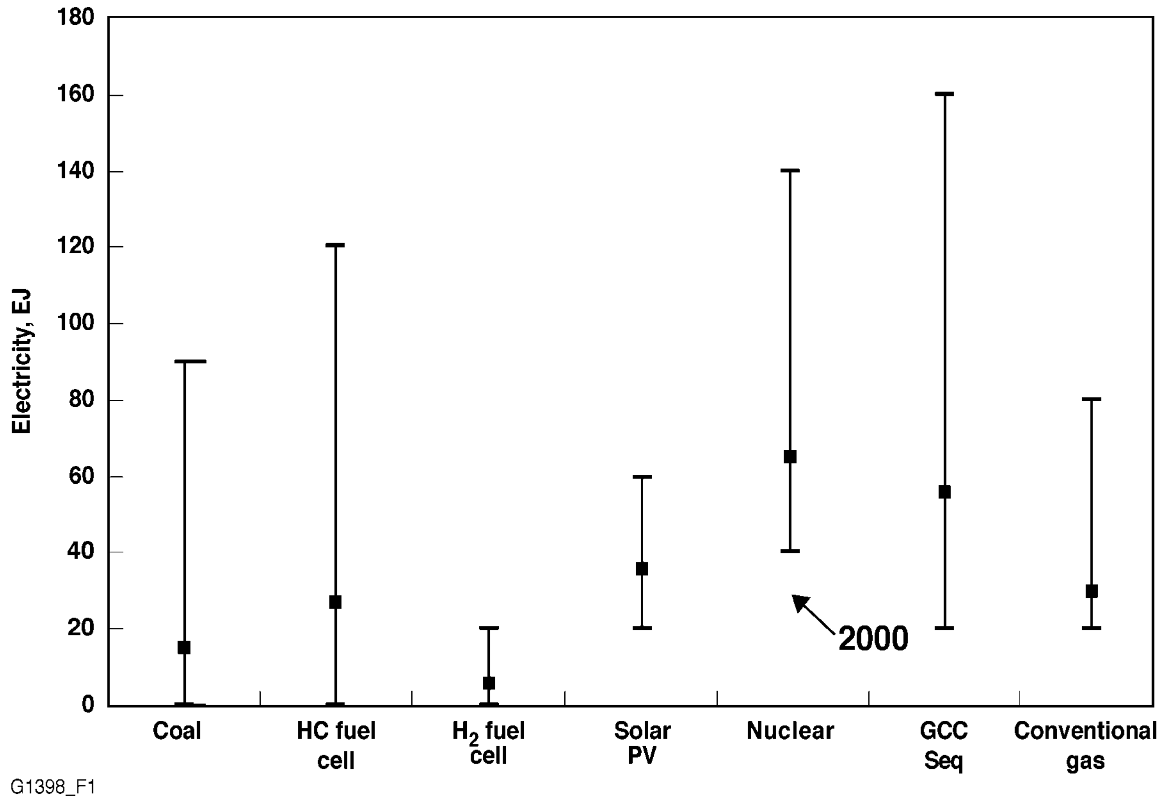

Figure 1. Ranges of Electricity Generation (EJ) Across 30 Scenarios for 2050.
Each bar shows the range across different IPCC scenarios for a given technology from upper to lower bound. Squares indicate the median value. GCC Seq is natural gas combined cycle with carbon sequestration, HC is hydrocarbon, and H_2 is hydrogen. The arrow indicates current global nuclear electricity generation. [Data from References 1, 3 and 5].

Two important conclusions are draw from Fig. 1. First, a serious examination by a large number of climate experts leads them to the conclusion that it will require a *range* of technologies to meet future global electrical power needs. Second, and very important for the purposes of our discussions, is that advanced nuclear power—assumed to cost more than today's nuclear electricity—is on average believed by the IPCC community to be the largest single contributor to the world's energy mix in 2050. The preponderant contributor, even at the bottom of the range, averaged over all technologies, is nuclear energy. Fifty years is a long time and many unexpected things can happen, but those thinking of investing money or careers in nuclear power should find these results encouraging.

Nuclear Technology—What Kind?

What type of nuclear energy is this likely to be? We might get some insight from the fact that roughly two-thirds of the energy increases are projected to occur in the developing world [4]. And a considerable part of this development by 2050 will almost certainly take place in East, Southeast, and South Asia, and in Latin America and the Middle East. This is illustrated in **Figure 2** by simply extrapolating what has been happening with regional energy usage over the past few years. There will, of course, be a need to replace existing plants and to support a level of growth in the developed world, but most of the overall growth can be expected in the developing world.

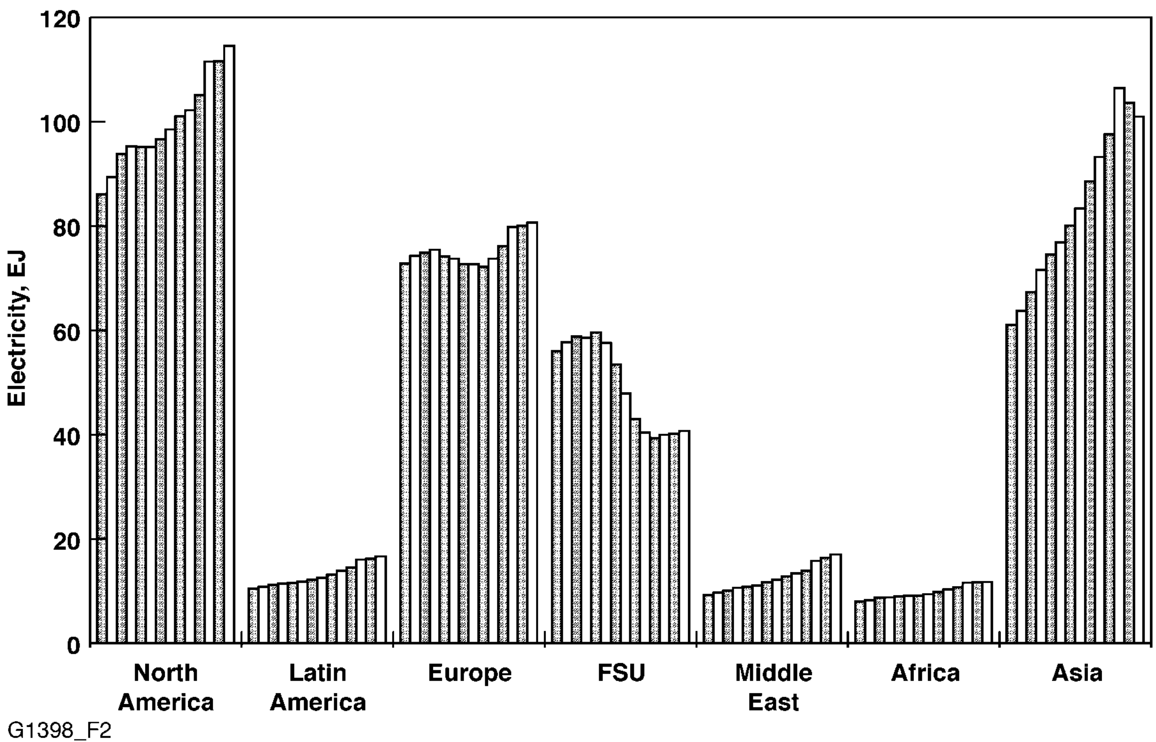

Figure 2. Energy Use from 1986 and 1999 for Seven Regions of the World.
FSU is the collection of states comprising the former Soviet Union [5].

So we should ask, what type of power are the societies of these countries likely to want and can afford? Part of the answer is seen by observing what is happening in the world to all types of systems. Miniaturization and modularization are becoming more and more prominent. Cellular telephones, personal digital assistants, aero-derivative gas-turbine power generators, fuel cells, and micro-turbine power units are all examples. This change is all part of a movement toward more efficiency, both energy and personal efficiency, driven by advances in micro- and nano-technology of materials. In electric power markets, decentralization and deregulation are having a similar impact. Small, efficient modular power plants are being installed on a district scale, decreasing the need for regional or national electrical transmission grids, which in any case are becoming harder and harder to site. Fuel cells, which a decade ago were big, cumbersome, and expensive, are now one-tenth as large and 50% more efficient.

The International Atomic Energy Agency has determined that small- and medium-sized nuclear reactors could fill the needs of developing countries, from power generation, through district and process heat, to the production of potable water [6]. They estimate that, by 2015, developing countries are expected to require almost 100 small- and medium-sized reactors, typically thought to center on the range of 100 to 200 megawatt-electric (MWe), and may be as small as 50 MWe and as large as 300 MWe. South Korea, China, Argentina, and Japan, among others, are developing reactors to fill this projected need. Not all of the new reactors to be added over the next 50 years will be small ones, but a significant number may be. Can they be made to compete in the marketplace? The answer lies in more than just cost—it also will be determined by convenience and reliability. People are willing and able to pay much more for cellular telephone service because of its convenience. People are willing to pay more for bottles of clean water than they pay for the same volume of gasoline.

Features of Small, Innovative Reactors

The recent report on the Geopolitics of Energy [7], released by the Center for Strategic and International Studies and chaired by former Senator Nunn and former Department of Energy Secretary 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. We would explicitly add inherently safe to this list.

Small nuclear-reactor technologies generally fit the criterion of modularity. The nuclear-reactor system should ideally be delivered to the site already assembled and not require refueling during its lifetime. This also means the reactor is already fueled when shipped to the site. Elimination of on-site refueling and fuel access would reduce proliferation concerns. This attribute can only be incorporated into a small reactor and should reduce the cost and complexity of the system.

For cost-competitiveness, it is helpful to look at today's electrical generation marketplace. A modern coal-fired power plant costs $1.50 per watt to build and 1¢ to 1.5¢ per kilowatt-hour (kWh) to operate. A small gas fired aero-derivative turbine plant costs 60¢ per watt to build and 3.8¢ per kWh to operate. A large modern nuclear plant costs between $1.50 to $2.00 per watt to build and around 1¢ per kWh to operate. This is the arena in which small nuclear plants will have to compete. The commercial designers of at least one small system, the Pebble Bed Modular Reactor (PBMR), claim that a 110-MWe module can be built and operated cheaper than these options [8]. Only time and experience will verify the claim. The PBMR is just one system that needs to be examined in more detail.

In general, the capital costs of small reactors should be reduced because of minimal containment size, simpler reactor control and refueling systems, and modular construction and factory fabrication. Operating costs should be lower because of higher fuel burnup 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.

These reactors should be capable of highly autonomous operation. All operations, from initial startup to final shutdown must be as autonomous as possible. Advanced instrumentation and control technologies coupled with the anticipated improvements in inherent reactor-control mechanisms in these low-power systems make realization of such goals possible. Operator actions can be limited to pressing a button to start the nuclear system and those actions necessary to operate the power conversion or other non-nuclear systems. For the remainder of the plant's operational life, the operator's primary function should be to monitor the status of the system. Significant cost savings would be associated with reductions in the number of highly trained staff at the site.

Small reactors lend themselves to incorporating safety features that reduce reliance of expensive active safety systems. Credible failures should be safely terminated by inherent mechanisms in the nuclear system without the release of radioactivity. Postulated severe accidents should be terminated without requiring emergency off-site responses. An approach to recover from such situations that permits recovery of the site should also be identified. This capability is a necessary corollary to achieving the staff reductions envisioned above.

Planned maintenance should be limited to non-nuclear, electrical, and control components easily accessed outside the reactor enclosure. Special attention must be given to eliminating instrumentation that is inherently short-lived because of temperature or radiation damage.

It is desirable to have replacement and disposal integrated into a system's design. One of the features inherent in the concept of no on-site refueling is that at the end of its core life, the entire reactor module is replaced. Innovative design incorporating the replacement, reconditioning, and disposal of expended reactor modules—including the disposition of spent fuel—is an important goal.

These are especially demanding goals likely achievable only with systems of relatively low power compared with large plants typical of modern construction. However, satisfying these goals has the potential to increase the security, safety, and public acceptance of the expanded use of nuclear power—one vision for small, innovative reactors.

One of the major challenges will be to accomplish these goals with an economically viable system. 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 to streamline the licensing process.

Large nuclear-power systems require complex emergency systems for heat removal and control, complex monitoring and control systems, extensive infrastructure for construction, operation, and maintenance, and a large electric grid to transport the generated electrical power. Small reactors, on the other hand, can be designed for unattended, high-reliability operation, factory manufacture and assembly is greatly facilitated, and the complexity of reactor safety systems can be simplified. Several associated benefits are enabled by small reactor size:

- As a result of simplified operations and reliance on autonomous control and remote monitoring, operating costs are lower.
- Development of new, small systems enables a comprehensive systems approach to nuclear-energy supply and infrastructure design, with all aspects of equipment life, fuel, and waste cycles included.
- Transportability by barge or ship enables factory manufacturing and reduced infrastructure requirements.
- No refueling or a replaceable core within a standardized modular design results in minimized fuel handling and enhances non-proliferation assurance.
- Large safety margins, high reliability, and reduced maintenance are enabled by resilient and robust designs.
- Waste minimization and waste form optimization can be built into the fuel cycle from the beginning.
-

Small Reactor Types

Table 1 lists some of the key parameters associated with various small innovative reactor concepts. Small reactors, like large ones, can be broken into several categories. One way to characterize them is by the type of cooling fluid. Several types use water and are described as small advanced light-water-cooled reactors (LWRs). These types stress enhanced safety, simplicity through fewer components, modular manufacturing, output in the range of 100 MWe, high fuel burnup thus reducing the amount of waste and enhancing the recycle time, and higher efficiency than current or planned LWRs, although not all types incorporate every feature. The core can sometimes be removed together with the vessel and the changeover done outside the host country. The Westinghouse IRIS system (International Reactor Innovative and Secure) is an example. South Korea is designing a small reactor mounted on a barge called SMART (Small Modular Advanced Reactor Technology).

Another technology much discussed today is the modular gas-cooled reactor using helium as the coolant and using a high-temperature gas turbine to generate power. One version of this concept uses fuel incorporated into graphite spheres containing fuel particles the size of billiard balls. These balls are called pebbles and contain micro-particles of protectively coated fuel. These pebbles are continuously fed into the reactor, and achieve very high burnup, making the spent fuel unattractive for weapons. They can be can be built in modules of approximately 100 MWe each. They typically have passive safety features that protect against postulated severe accidents. Another type of gas-cooled graphite moderated reactor, the Modular High-Temperature Gas Reactor (MHTGR), uses fuel elements in the shape of hexagonal graphite blocks and is periodically refueled off-line.

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.

A third type of small reactor uses liquid metal as the coolant. The low vapor pressure of the metal coolant permits the use of thin-walled reactor vessels that make the factory-assembled system lighter in weight and more easily transported. These reactors are not moderated and operate with a neutron energy spectrum much higher than reactors moderated with water or graphite and cooled with water or gas. This supports high internal conversion of fertile to fissile materials and the potential for a very long core life. The liquid metal coolant with the most experience is sodium, but lead–bismuth alloys have also been used, and lead is being considered by the Russians [see for example Reference 9].

Other concepts are in various stages of development. Molten salt has been considered both as a coolant and as a fuel. Cooling with heavy water is also being considered and the heavy water serves as both as a moderator and as a coolant. Another idea uses a cylindrical core of thorium, a fertile material that can be transmuted very slowly to fissile uranium-233. The reaction continues in a controlled fashion, beginning at one end and continuing to the other much like a candle burning [10].

Other Applications

In addition to the generation of power, small nuclear reactors also have other important potential applications, which may or may not be coincidental with the generation of electricity. These applications include the desalination of seawater, the decontamination of polluted water, the use of the heat for co-generation of electricity or district heating or for industrial process heat, and the generation of hydrogen by electrolysis during off-peak periods for subsequent regeneration in fuels cells either for grid power or to power vehicles.

Obstacles to Overcome

To commercialize any small nuclear-reactor technology, a series of steps are necessary, but may not be sufficient. An R&D program must be sufficiently funded to be sustainable and to attract serious researchers and serious industrial interest. At this stage, industry's interest and not their funding is necessary. At the appropriate moment, there must be a demonstration of the technology and industry must be involved in the demonstration for two reasons—the amount of money needed goes up and the commercialization potential requires its first real test, and governments, at least in free-market economies, cannot do that. Then comes the so-called "Valley of Death" or the test of whether an industry will pick up the technology and try to commercialize it, providing the necessary capital and identifying the markets. To reach this stage, commercial industry must feel that it owns a significant share of the intellectual property, and therefore can make a reasonable profit from its investment. This is not easily accomplished if governments have been involved and own the property rights to the technology.

First, however, we should focus on what is needed from R&D. A recent report by the Department of Energy's Nuclear Energy Research Advisory Committee made some suggestions along these lines [11]. While focused on the proliferation aspects, they are general enough to be broad indicators of R&D:

- Extending core life
- High-burnup, high-neutron-flux fuel assemblies
- Structural materials in harsh environments for long periods
- Low-maintenance components, such as pumps and steam generators
- Installation of pre-fueled and sealed systems
- Transporting reactor core before and after use
- Loading and unloading fuel in a proliferation-resistant manner
- Remote monitoring and diagnostics of operations
- Experimental demonstrations

Beyond R&D and the demonstration of particular concepts, commercialization will have to overcome hurdles dealing with the regulatory, environmental, and health aspects, and research is required on these aspects as well. In addition, considerations of financing, whether through the World Bank or other sources, will have to be thought out well in advance—many developing countries are unlikely to be able to afford power plants, whatever the type, on their own.

International Collaboration

It is obvious that a program in small nuclear technology, which has a substantial part of its product focused on markets in the developing world, must be international in nature. The size of the potential market, the existing extent of the technology among the developed nations, the importance of energy to the world economy, the need for a diverse set of supply options, the regional and global effects of emissions from power plants—all argue that this must be an international endeavor. The question is how to form and implement it.

If small reactors are going to meet a need and succeed commercially, then it would be very advantageous to have a smaller number of options than shown in Fig. 1, rather than a large number of options early on in the cycle. Finally, it is absolutely necessary to have the developing countries involved. They will not, in general, be receptive to others bringing them the "riches" of a new technology—and as important users of the technology, their input is needed as early as possible.

Path Forward

There are a number of small-reactor-development efforts underway with differing economic, political, and social goals. A process of seriously examining the potential of each concept is very important, and the workshop held at the Baker Institute in March of 2001 is a very good beginning [12]. It is the first step on a long trajectory, populated with many issues and barriers to the realization of this energy source. It is only a preamble that hopefully motivates us to take the next step of exploring how small, innovative reactor technology can be successfully actualized in the emerging global-energy enterprise.

What might we do as an outgrowth of this workshop? We would suggest first identifying the critical issues and barriers to the success of this technology, and how such obstacles can or cannot be overcome. We have an unusual opportunity to avoid the pitfalls of technology development without sufficient knowledge, support, and acceptance by the public and government. We should work together as a community—the government, business, and public sectors that develop science, policy, and technology. The immediate objective should be to identify a path forward having sufficient support from industry, government, and users, leading to a sustainable international development and deployment program.

Acknowledgments

We are grateful to Edwin Jones for a number of suggestions, especially on desirable paths forward, which have been incorporated into our thinking. Gorgiana Alonzo provided us with timely, excellent editorial assistance in preparing this manuscript.

References

1. N.J. Nakicenovic, G. Alcamo, B. Davis, J. Fenhann de Vries, et al., *Special Report on Emissions Scenarios*, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, U.K., 2000).

2. *Electricity Technology Roadmap*, Electric Power Research Institute, Palo Alto, California, 1999.

3. N. Nakicenovic and K. Riahi, *An Assessment of Technological Change Across Selected Energy Scenarios*, Report to the World Energy Council (London), to be published, 2001.

4. *Energy for Tomorrow's World*, World Energy Council, London (St. Martins Press, New York, 1993.)

5. *BP Amoco Statistical Review of World Energy*, BP Amoco, London. Web site address: www.bpamoco.com/worldenergy.

6. "Introduction of Small and Medium Reactors in Developing Countries," *Proceedings of IAEA Advisory Group Meetings*, 23–27 Oct 1995 in Rabat, Morocco and 3–6 Sept 1996 in Tunis, Tunisia, International Atomic Energy Agency, Vienna.

7. *The Geopolitics of Energy in the 21st Century*, Center for Strategic and International Studies, Washington DC, 2001. Web site address: www.csis.org/sci/geopoliticsexecsum.pdf.

8. M. Popper, "A Second Chance for Nukes in America?" in *Streetwise, BusinessWeek Online*, February 20, 2001.

9. *White Book of Nuclear Power*, E.O. Adomov, ed., Research and Development Institute of Power Engineering (NIKIET), Moscow, 1998.

10. E. Teller, M. Ishikawa, L. Wood, R. Hyde, and J. Nuckolls, *Completely Automated Nuclear Reactors for Long-Term Operation II*, 1996 Conference on Emerging Nuclear Energy Systems (ICENES ’96), Obninsk, Russian Federation. Also available from Lawrence Livermore National Laboratory, Livermore, California, publication UCRL-JC-122708-PT 2 (1996).

11. *Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS),* Report by the TOPS Task Force of the Nuclear Energy Research Advisory Committee (NERAC) of the U.S. Department of Energy, January 2001. Web site address: www.nuclear.gov/nerac/neracoverviewla.html.

12. Workshop on Nuclear Energy Technologies: A Policy Framework for Micro-Nuclear Technology, James A. Baker III Institute for Public Policy, Rice University, Houston TX, March 19–20, 2001.