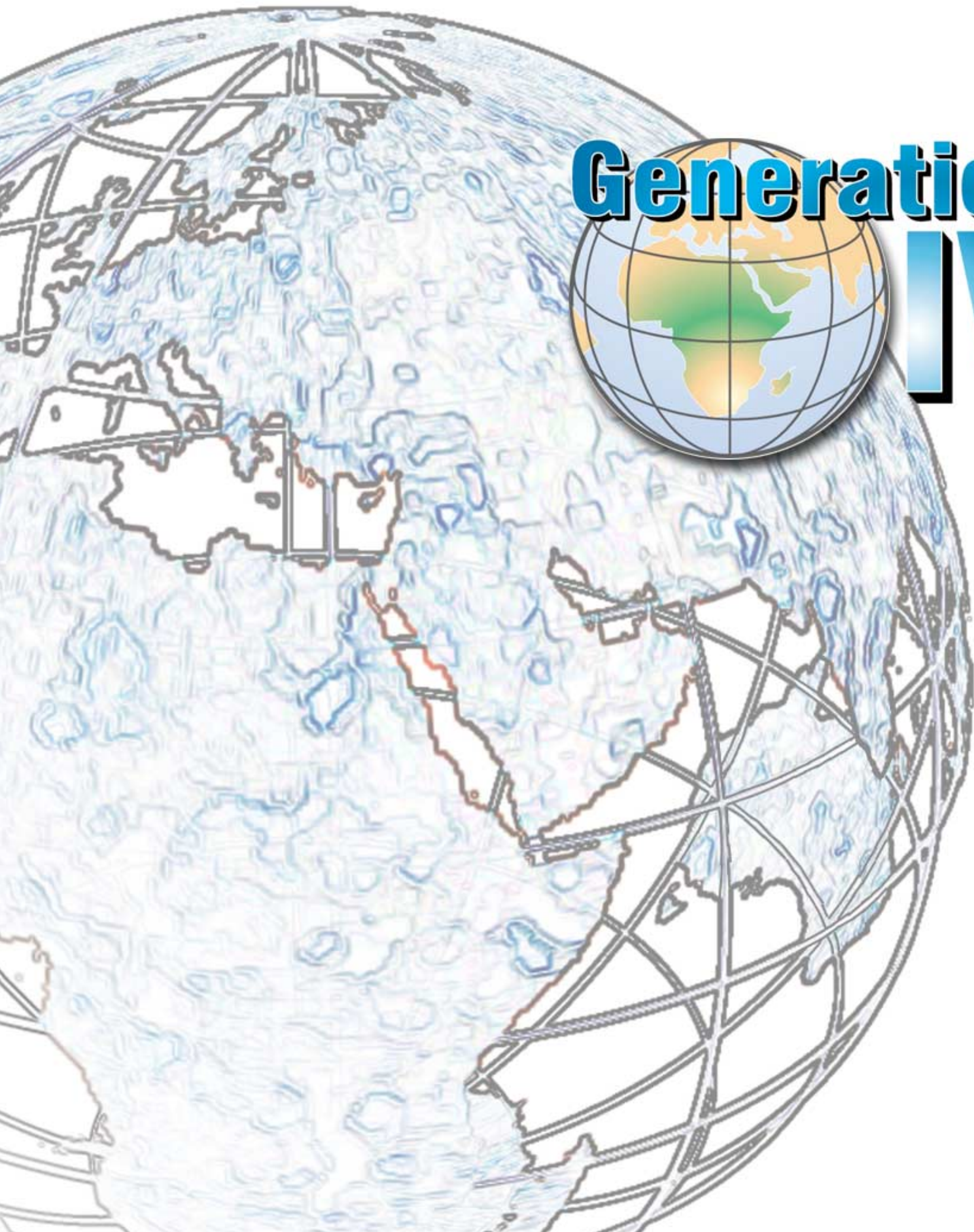
Discussion on Goals for Generation IV Nuclear Power Systems

from a Workshop held
May 1–3, 2000



July 31, 2000

Industry Perspective Presentation
at the Generation IV Workshop
May 1–3, 2000
Bethesda, Maryland.

Executive Summary

Introduction

The United States Government believes that nuclear power must remain a viable option to meet present and future energy supply needs. To help achieve this goal, the U.S. Department of Energy (DOE) has encouraged a wide-ranging discussion on the development of next-generation nuclear power systems — known as Generation IV — to engage governments, industry, and the research community world wide.

As a preliminary step, DOE sponsored the Generation IV Workshop, attended by nearly 100 U.S. and international experts from the nuclear industry, academia, national laboratories, and international government and nongovernment organizations. The purpose of the Workshop was to make recommendations to DOE on goals that Generation IV nuclear power systems should strive to meet in order to offer a viable future nuclear energy option for developed and developing countries of the world.

The Department of Energy has determined that its next step in the Generation IV initiative will be to prepare a technology roadmap to guide the Generation IV effort in the United States. The Department will use recommendations from the Workshop as principal input to guide the development of the Generation IV technology roadmap. The DOE encourages other interested countries to conduct their own comparable roadmapping activities, the results of which can then be pooled to assist in making decisions about future research activities.

Generation IV Initiative

Recognizing the challenges facing nuclear power as we enter the 21st century, DOE believes the time has come to lay the groundwork for the next generation. This means developing technologies that offer a nuclear power option that is economically competitive in many markets while making further advances in safety, waste minimization, and proliferation resistance.

Nuclear energy research programs in other countries have begun developing concepts that could form the basis for Generation IV. In the United States, for example, the Nuclear Energy Research Initiative (NERI) program is investigating a range of innovative concepts that hold potential to address all of the factors inhibiting the future expansion of nuclear power.

Safety Presentation at the Generation IV Workshop.

Goals of the Generation IV Initiative

While DOE is examining desirable goals for Generation IV, a common thread through the Workshop was that the goal of the Generation IV effort should be the following:

Design one or more nuclear power systems that can be licensed, constructed, and operated in a manner that will provide a competitively priced supply of electricity while satisfactorily addressing nuclear safety, waste, proliferation, and public perception concerns of the countries in which it is deployed.

Desired State in Twenty Years

Extensive discussion at the Workshop centered on the question of what a Generation IV initiative should plan to achieve by the year 2020. A broad range of viewpoints were presented at the meeting. The median of the viewpoints reflected two principal factors. The first was the recognition that government and industry funding for R&D in general, and nuclear power R&D in particular, is and will continue to be scarce in many countries. The second was the belief that unless the intent is to adopt aggressive goals and have one or more Generation IV prototype plants in operation by 2020, the program will be too diffuse and unfocused to generate substantial interest. Operating one or more prototype plants by 2020 would allow large-scale deployments in 2030 and beyond — the time when the bulk of the Generation II nuclear power plants reach 60 years of age.

Proposed Performance Goals for Generation IV Nuclear Power Systems

The Workshop examined goals that Generation IV nuclear power systems should meet in order to be a viable and preferred energy system in the global economy about 20 years from now. At this early stage, these goals should be considered desired performance targets rather than firm system requirements.

Competitive Busbar Cost of Electricity	*The busbar cost of electricity from a Generation IV system must be competitive with other electricity-generation sources in the region or country in which the plant is located. (As an example, the competitive cost of electricity projected for the United States is 3 cents/kWh expressed in constant 2000 dollars.)*
Acceptable Risk to Capital	*The risk to capital for a Generation IV project must be attractive with respect to other major capital investment projects in the markets of the region or country, including both the amount of investment required and the risk to the investment. (As an example, an attractive level of investment size and risk projected for the United States could be achieved for a plant capital investment of $1000/kWe or less.)*
Limited Project and Construction Lead Times	*The length of time that the project spans from placing the contract for a Generation IV plant purchase to the first electric revenues (project lead time) must be less than four years. As a part of this goal, the time that the project spans from the first concrete pour to reactor startup tests (construction lead time) must be less than three years.*
Low Likelihood of Core Damage	*Generation IV reactors must have a very low likelihood of core damage.*

Demonstration of No Severe Core Damage	*Generation IV reactors must demonstrate that severe core damage will not occur for any plausible initiating event. This demonstration must be accomplished through integrated reactor testing.*
No Need for Offsite Response	*No credible scenario should exist for release of radioactivity requiring offsite response to ensure public safety.*
ALARA Radiation Exposure	*Generation IV reactor designs must afford ALARA radiation exposure over the total system lifetime.*
Tolerant of Human Error	*Generation IV reactors must be highly tolerant of human error.*
Solutions for All Waste Streams	*Generation IV systems must have complete waste solutions for all waste streams.*
Public Acceptance of Waste Solutions	*Politically and publicly acceptable solutions must exist for all nuclear waste streams and an implemented solution must exist for wastes from previous and existing plants.*
Minimal Waste	*Generation IV systems must minimize waste to the extent practical.*
Minimal Attractiveness to Potential Weapons Proliferators	*Development of Generation IV systems should preserve the current regime, where the misuse of the civilian nuclear fuel cycle is the least attractive route to potential weapons proliferators. This applies to both indigenous facilities and to exported components of the fuel cycle.*
Intrinsic and Extrinsic Proliferation Resistance	*Generation IV system design should rely on intrinsic proliferation resistance features to the maximum extent possible. Extrinsic barriers should complement them in a manner tailored to the specific fuel cycle.*
Evaluation of Proliferation Resistance	*Generation IV designs must be evaluated for proliferation resistance relative to established guidelines.*

The Path Forward for a Generation IV Program

The time is right to begin a focused program to develop the next generation of nuclear power systems. Concerns over energy resource availability, climate change, air quality, and energy security point to a clear need for future nuclear power generation. While the current Generation III nuclear power plant designs provide an economically, technically, and publicly-acceptable electricity supply option in many markets, further advances in nuclear power system design can broaden the opportunities for the use of nuclear power.

To define the technical challenges involved in pursuing Generation IV, the U.S. Department of Energy (DOE) plans to develop a technology roadmap to guide its Generation IV efforts and encourages similar roadmapping activities in other countries. The DOE roadmap will be undertaken in fiscal year (FY) 2001. The research called for in the roadmap would enable selection of one or more promising Generation IV system concepts for further development.

Contents

Introduction

The United States Government believes that nuclear power must remain a viable option to meet present and future energy supply needs. To help achieve this goal, the U.S. Department of Energy (DOE) has encouraged a wide-ranging discussion on the development of next generation nuclear power systems — known as Generation IV — to engage governments, industry, and the research community worldwide.

As a preliminary step, DOE sponsored a Generation IV Workshop, held May 1–3, 2000 in Bethesda, Maryland. The Workshop was attended by nearly 100 U.S. and international experts from the nuclear industry, academia, national laboratories, and international government and nongovernment organizations. The purpose was to define the desired goals and characteristics that Generation IV nuclear power systems should strive to meet in order to offer a viable future nuclear energy option for the developed and developing countries of the world.

Participant Breakout at the Generation IV Workshop.

The goals for Generation IV are performance targets that the future nuclear power system should meet to be a viable and preferred energy system in the global economy about 20 years from now. The *characteristics* for Generation IV are specific qualities, features or performance levels that directly enable the future nuclear power system to meet its goals. At this early stage, the characteristics should include all promising approaches to Generation IV.

This document presents the outcome of the Workshop. The recommendations represent a general consensus of the participants at the Workshop. It is important to note that unanimous agreement was neither obtained nor required for the recommendations herein. This report should not be construed as an endorsement of the recommendations by any specific person or organization present at the Workshop.

The Department of Energy plans to prepare a technology roadmap to guide its Generation IV efforts. DOE will use this Workshop report as input to guide the development of the Generation IV technology roadmap. The roadmapping proposed by DOE is described later in this document and establishes a potential path forward for a Generation IV technology research and development program.

An Overview of the Generation IV Initiative

Generation IV is an initiative first suggested by the DOE Office of Nuclear Energy in June 1999. Accordingly, an overview of the reasons for the initiative and its future direction is given for proper perspective. The following two subsections are drawn almost entirely from a Generation IV concept paper issued by DOE in January 2000 for a meeting of senior representation of nine countries.[1]

Issues Facing the Future Use of Nuclear Energy

The four primary challenges facing the future expansion of nuclear energy — competitive economics, nuclear power plant safety, nuclear waste, and proliferation of weapons materials[2] — continue to occupy government and industry policy makers and significant segments of the public.

Regarding economics, the performance of nuclear power has been mixed. On the positive side, it was just a few years ago that energy analysts were predicting the wholesale closure of nuclear power plants world-wide as competitive pressures from a rapidly deregulated energy market take hold. They have been proven to be wrong. In the United States, the average production costs of nuclear power generation are competitive with the costs of producing electricity from coal, oil, or natural gas. In 1998, six of every ten nuclear power plants operating in the United States had electricity generation costs of less than 2 cents per kilowatt-hour, in a market priced from 4 to 6 cents per kilowatt-hour.[3]

Indeed, electric industry restructuring in the United States is leading to the consolidation of the nuclear utility industry. Utilities that have proven their ability to run their plants safely and cost efficiently are buying nuclear plants from other utilities, to the advantage of both. This development has positive implications for both the future of current plants and the prospects for future plants.

On the other hand, the Three Mile Island accident made clear to the financial community the vulnerability of existing nuclear plants to fiscally catastrophic failure. As one observer put it, "the fundamental lesson that Wall Street learned from Three Mile Island was that a group of NRC-licensed operators — not appreciably better or worse than any other crew — could turn a $2 billion asset into a $1 billion cleanup job in about 90 minutes."[4] This type of concern is very much alive and affects the risk premium of capital accessibility of nuclear plant construction. For electric utilities, avoiding near-term economic risk will in many cases outweigh long-term needs. Thus,

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1 U.S. Department of Energy, Office of Nuclear Energy, Science and Technology, "Generation IV: Looking to the Future of Nuclear Power," January, 2000.

2 President's Committee of Advisors on Science and Technology (PCAST), Panel on Energy R&D, "Report to the President on Federal Energy R&D for the Challenges of the Twenty-First Century," available at www.whitehouse.gov/WH/EOP/OSTP/Energy, November 1997.

3 *Nucleonics Week*, McGraw-Hill Companies, Vol. 40, No. 27, July 8, 1999.

4 Peter A. Bradford, Chairman, New York Public Service Commission, letter to Dr. Irwin Seltzer, Energy and Environmental Policy Center, Harvard University, January 13, 1989.

in addition to its importance for public health and environmental protection, reactor safety has an important bearing on investment protection.

Additionally, the capital cost of an advanced light water reactor is currently about $1500 to $1800 per electric kilowatt, as compared to about $500 per kilowatt for a natural gas-fired plant.[5] One clear result of this will be increased near-term reliance on natural gas for electricity generation. Natural gas is projected to be readily available for many decades (but at higher prices as demand increases). Unlike the current generation of nuclear plants, gas-powered plants are quick to build. They are also highly efficient compared to a typical nuclear plant and require minimal staff to operate. Furthermore, natural gas in the United States is not burdened with extensive regulatory oversight and has not been forced to internalize the full disposition cost for its *spent fuel* (*i.e.*, greenhouse gases and other air pollutants). In the United States and in many countries abroad, if nuclear plants are to compete on economics, they must compete against natural gas.

Regarding safety, the Chernobyl accident in the Ukraine underscored the importance of proper design, operation, and regulatory practices to the future use of nuclear power. Western-designed and -built commercial nuclear power plants have proven their ability to sustain major internal damage without major impacts to the environment, as demonstrated by the Three Mile Island accident in the United States. In addition, there has been a dramatic improvement in the operating performance of the commercial power plants in the West since the Three Mile Island accident. For example, in 1999, U.S. nuclear power plants achieved an average capacity factor of about 85%, 27 percentage points higher than the 1980 average. Collective radiation exposure has trended sharply downward, and is now at about 25% of 1980 levels. Industrial safety accident rates have seen a near tenfold improvement since 1980 and are about 91% lower than the average accident rates for U.S. private industry.[6]

Regarding waste, solutions to the problems of spent fuel and high-level waste disposal have been elusive. Nuclear power offers a clear advantage in that it generates a fraction of the waste volume generated by fossil fuel-based technologies. Emplacement of high-level nuclear wastes into deep geologic formations has gained acceptance among the technical community (if not the public) as a satisfactory, if not perfect, solution. However, until permanent repositories are actually constructed, licensed, and operated to store these wastes, the long-term viability of nuclear power will continue to be questioned.

Overall, the safety and environmental record of nuclear power can factually be described as excellent, even without a long-term solution to the high-level waste problem. Despite this, nuclear power remains, in the perception of some, a dangerous and polluting technology. However undeserved this perception, the underlying

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5 George Booras, "Cost of Electricity and Economic Issues," Electric Power Research Institute, Electricity Supply Workshop, Palo Alto, April 9, 1998.

6 Nuclear Energy Institute, *U.S. Nuclear Power Plant Performance*, available at www.nei.org/library/facts.html, September 1999.

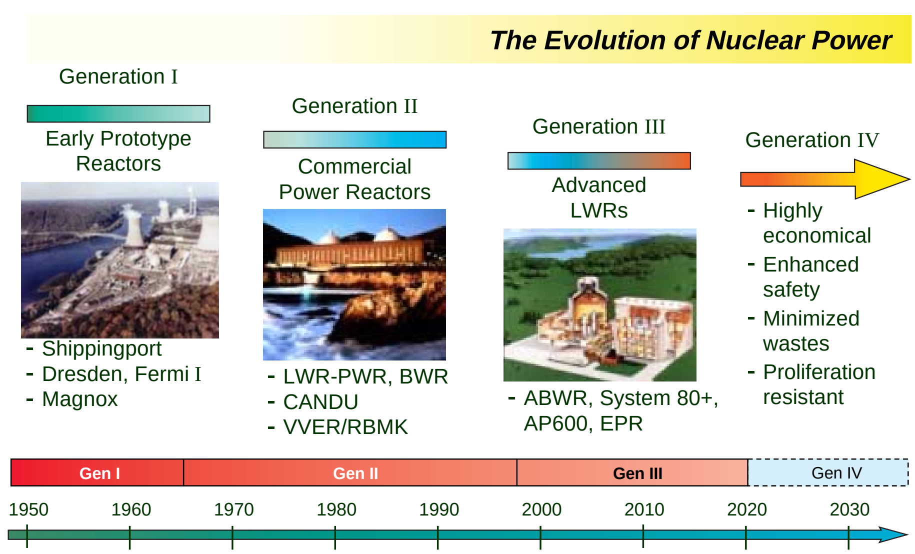
concerns need to be addressed if nuclear power is to play a significant role in future energy supply.

Regarding proliferation resistance, fissile materials within civilian nuclear power programs are adequately safeguarded by an effective, international system. However, it would be beneficial if future nuclear fuel cycles and nuclear materials safeguards systems could provide an even higher degree of resistance to nuclear material proliferation or diversion. For example, analogous to the concept of *passive safety*, perhaps *intrinsic safeguards* characteristics might be of value in future nuclear power research and development. The United States plans to invest part of its nuclear energy R&D effort into developing nuclear power and safeguards technologies that reduce the proliferation concern.

Generation IV Initiative

Nuclear power plants now commercially available are regarded, by most counts, as the third generation of nuclear power plant design. The early, rather small Atoms for Peace-era plants comprised the first generation, and most are now shut down. The second-generation plants represent the majority of the nuclear plants now in operation, both in the United States and abroad. The third generation could be viewed as beginning with the Advanced Boiling Water Reactors in Japan and the System-80 plants in Korea. Generation III now includes the Advanced Light Water Reactors (ALWRs) and the European Pressurized Reactor (EPR) that emerged from public-private cooperation in the 1980s and early 1990s, and has a firm market for the next decade or more, mostly in Asia.

Generation III reactors do achieve significant improvements in safety and simplicity of operation. The main problem for these reactors in the United States and other markets is that they were designed to meet the requirements of regulated U.S. utilities that were guaranteed reimbursement of all allowable costs. Reducing construction and operating



costs was a consideration but not a primary concern. Consequently, the life-cycle cost to construct, operate, and decommission an ALWR plant in the U.S. is estimated at about 4.5 cents per kWh. With the change toward deregulation in U.S. electricity generation, it is estimated that a new nuclear power plant design will have to offer a life-cycle cost of about 3 cents per kWh to be competitive. As a result, these evolutionary and advanced designs are today not cost-competitive with gas-fired plants.

Recognizing both the achievements and shortcomings of Generation III reactors and the opportunities for their improvement, it is now time to lay the groundwork for the next generation. This means developing technologies that provide a nuclear option that is economically competitive in an increasing number of markets while making further advances in safety performance, waste minimization, and proliferation resistance. In addition, further advances to existing light water and other reactor technology should also be pursued, because it is clear that further advances to light water reactor technology represent the most likely candidate for near-term deployment of new nuclear plants outside the United States. For example, by using risk-assessment tools and risk-informed regulations to simplify these plant designs by eliminating unnecessary systems, and by using advanced component fabrication and assembly techniques, it may be possible to reduce costs to make these plants more attractive.

The time is right to begin a focused program to develop the next generation of nuclear power systems. Concerns over energy resource availability, climate change, air quality, and energy security point to a clear need for future nuclear power generation. While the current Generation III nuclear power plants provide an economically, technically, and publicly acceptable electricity supply option in many markets, further advances in nuclear power system design can broaden the opportunities for the use of nuclear power.

Nuclear energy research programs worldwide have begun developing concepts that could form the basis for Generation IV. Through its Nuclear Energy Research Initiative (NERI) program, the United States has also begun investigating concepts such as small/modular reactor designs, proliferation-resistant designs, and other concepts that hold the potential to contribute to Generation IV. However, small programs like the NERI program can only serve as a *birthing place* for these new ideas. Large-scale development of these or other nuclear energy concepts can best be accomplished through a focused and coordinated international effort with greatly increased U.S. and international government and industry participation.

The Goals of the Generation IV Initiative

Considerable discussion at the Generation IV Workshop addressed the appropriate goals for Generation IV. A broad range of opinions is offered on this subject, reflecting the diversity of experiences of the participants. While there is no formal statement of a goal for Generation IV from the Workshop, a common theme is that the goal of the Generation IV effort should be the following:

"Design one or more nuclear power systems that can be licensed, constructed, and operated in a manner that will offer a competitively priced supply of electricity while satisfactorily addressing nuclear safety, waste proliferation, and public perception concerns of the countries in which it is deployed."

Desired State in Twenty Years

Workshop participants addressed what a Generation IV initiative should plan to achieve by the year 2020. Since no single majority viewpoint was evident at the Workshop, a summary of viewpoints expressed at the meeting is presented here. The meeting participants generally hold one of three differing views of what a Generation IV program should achieve by 2020.

The first view is driven by a concern that unless significant progress toward new plant construction is made in the very near future, the infrastructure needed to support large-scale deployment of nuclear power plants will continue to erode. Participants sharing this concern generally believe that a Generation IV program should strive to complete the design and begin construction of one or more prototype plants before 2010, even if this means that the goals lead to evolutionary improvements instead of revolutionary solutions.

The second view holds that goals should lead to revolutionary solutions in order to stimulate interest and renew acceptance of nuclear power. Accordingly, there is an underlying concern that, owing to lack of government and industry support for R&D (especially in the United States), regulatory uncertainties, a relative lack of technical maturity of several promising Generation IV concepts and other issues, it will not be possible to begin building a prototype plant until 2020 at the earliest.

The third view shares elements of the first and second views, and best represents the median of the viewpoints. Participants holding this third view generally recognize that federal and industry funding for nuclear power R&D will continue to be scarce in many countries. However, they also believe that unless the intent is to adopt aggressive goals and have one or more Generation IV prototype plants in operation by 2020, the program will be too diffuse and unfocused to generate substantial interest. This, in turn, will lead to a shortfall in resources and facilities necessary to support the program, and the program will not succeed. These participants believe that the objective should be to have one or more prototype plants built and operating by 2020. This, in turn, would allow large-scale deployments in 2030 and beyond — at the time when the bulk of the Generation II nuclear power plants reach 60 years of age.

Note that the key variable influencing these three points of view is the expected level of governmental and industry support. One participant observed that the U.S. nuclear power program went from building the world's first nuclear reactor (CP-1) to building a commercial prototype (Shippingport) in about 15 years with strong government, political, and financial support. With adequate support, any of the above scenarios are possible.

Proposed Goals for Generation IV Nuclear Power Systems

Fourteen goals are proposed for Generation IV nuclear power systems. At this early stage, these goals should be considered performance targets rather than firm system requirements.

Competitive Busbar Cost of Electricity

The busbar cost of electricity from a Generation IV system must be competitive with other electricity-generation sources in the region or country in which the plant is located. (As an example, the competitive cost of electricity projected for the United States is 3 cents/kWh expressed in constant 2000 dollars.)

The busbar cost of electricity is the chief economic goal on Generation IV nuclear power systems because it is believed to be the single most important measure of competitiveness for future electricity supplies. Other economic criteria are found in the goals and characteristics, but almost all of them are direct factors in the busbar cost. The factors in the busbar costs are discussed below.

The analysis of busbar costs is generally divided into two portions: first is the determination of the owner/operator life cycle cost. Life cycle costs are divided into four major areas, which are intended to include all monetary costs. The four areas are (1) capital costs, including both the capital required to build the system, owner's costs, and the cost of financing, (2) operation and maintenance (O&M) costs, including conventional costs and the costs of regulation and insurance, capital additions during life, and general and administrative expenses, (3) fuel cycle costs, which include all front- and back-end fuel cycle costs, and (4) decommissioning costs, which are typically either included in the capital or O&M cost areas. The second portion of the analysis is the determination of the unit busbar cost, expressed in cents/kWh. This requires incorporating various financial assumptions for the project, such as the discount rate, financing mix and costs, project lead time, and the projected book life, tax life, and tax rates of the plant.

A number of important assumptions were identified relative to the analysis of busbar cost:

1. Any successful Generation IV system will be deployed in a variety of regions and countries and on a scale where economies of volume are achieved.

2. The cost of research, design, development, and demonstration (RDD&D), including the cost of advancing along the *learning curve* for the system, should not be included in the busbar cost analysis of a mature system. In

general, this means that the busbar cost analysis is done for the Nth such plant being built and operated. It is suggested that N = 5 has advanced along the learning curve sufficiently and is likely to afford economies of volume production of the plants to be reflected adequately in the analysis. It is recommended that the investment requirements for RDD&D and advancement along the learning curve should be made by contributions from government and industry.

3. Some flexibility is needed in defining the investors in the project to build and operate a Generation IV plant in order to adequately reflect future trends. For example, the investors could be owner/operators, vendors, or, even, third-party investors. Accordingly, the rate of return on the investment and the exposure and duration of risk to that capital need to properly reflect the opportunities open to this wide class of investors. There may also need to be modifications to this goal that reflect the economics of clustered units and incremental capacity additions.

4. It is generally assumed that electricity providers 20 years from now will operate as merchant plants in highly deregulated markets worldwide. However, in order to reflect all outcomes, the economic analysis should be based on either merchant plant or regulated utility assumptions as projections indicate for each specific region or country.

An important modification to this goal exists for Generation IV plants that produce additional revenues from the production of process heat, hydrogen, or other processes and products. In these cases, the energy byproducts yield revenues that will serve as a credit against the busbar electricity cost. This even extends to the extreme where a plant may produce no electricity at all.

Acceptable Risk to Capital

The risk to capital for a Generation IV project must be attractive with respect to other major capital investment projects in the markets of the region or country, including both the amount of investment required and the risk to the investment. (As an example, an attractive level of investment size and risk projected for the United States could be achieved for a plant capital investment of $1000/kWe or less.)

This goal reflects the need to be able to attract sufficient investment in any Generation IV plant to meet its capital requirements in a competitive capital market. The definition of plant capital cost in this goal is the overnight capital cost plus owner's costs (e.g., for land). Although this goal is specified as the unit capacity cost ($/kWe), the total capital investment is more important to financial markets, so that smaller plants may appear to more easily meet this investment risk goal. Of course, a growing demand for electricity may require a cluster of small modules to meet the project's overall capacity needs.

While the cost of capital and a number of other factors are common to this goal and the busbar cost goal, both goals are essential to meet.

Limited Project and Construction Lead Times

The length of time that the project spans from placing the contract for a Generation IV plant purchase to the first electric revenues (project lead time) must be less than four years. As a part of this goal, the time that the project spans from the first concrete pour to reactor startup tests (construction lead time) must be less than three years.

This goal reflects a consensus that the time to complete nuclear power plant projects and bring them on line must greatly improve to enable them to again become a preferred option for electric capacity worldwide. Specifically, two measures of the time to construct are recommended, one for the total project lead time and one for the construction lead time. The project lead time spans the time from completion of the contract for the purchase of the system to bringing the plant into commercial operation. This corresponds to the planning horizon of the plant operator and may encompass substantial investments for factory-produced units.

The construction lead time is typically a major portion of the project lead time and spans the time from mobilizing construction for the first concrete pour until the plant is ready for fuel loading. This corresponds to the length of time a majority of the financing is at risk. Of course, this definition would need to be modified for plant concepts that do not require onsite construction or fuel loading. This definition also needs to be modified for a plant made up of several smaller modules, as appropriate.

Note that these lead times have a dominant effect on the risk to capital and busbar cost goals. They are important enough to warrant being a goal and are tightly coupled to many of the others.

Low Likelihood of Core Damage

Generation IV reactors must have a very low likelihood of core damage.

There is widespread consensus that Generation IV reactors should be extremely resistant to core damage accidents. A majority believe that measurable improvements in resistance to potential core damage accidents must be a feature of Generation IV systems. This position is not driven by a belief that current light water reactors are in any way unsafe or that current light water reactors pose unacceptable public risks. Rather, it is the belief that reducing the likelihood of core damage is achievable without undue cost, and that the public needs assurance that core damage accidents will not occur in Generation IV (particularly with widespread deployment), and that investors can be attracted by lowered risk to their capital investment (since a serious accident in one reactor can adversely impact all others).

While there is widespread consensus for such a goal, it is acknowledged that current light water reactors already meet the goal of a low likelihood of core damage, and, thus, more stringent safety goals are unnecessary to ensure safety. Those concerned suggest that the basis for safety performance has been established, and any quantitative reduction of core damage frequency would serve no useful purpose.

Noting that current U.S. Nuclear Regulatory Commission requirements specify that advanced light water reactor designs must have a core damage frequency of less than 10^{-5} per reactor year, a majority believe that Generation IV reactors must show the ability to exceed this goal. The aim of this belief is a focus on ensuring a high resistance to core damage and on demonstrating measurable safety improvements over the current generation of advanced light water reactors.

It is noteworthy that the consensus goal described above has been forged from widely divergent viewpoints. Views range from holding that current reactors are *safe enough*, to prescribing that there should be no possibility of a core damage accident in a Generation IV reactor. Some participants even suggest that no formal goal related to the likelihood of core damage is necessary, and that the principal safety goal should be expressed in terms of the product of accident frequencies and their associated consequences (i.e., *offsite risk*). While most participants recognize the technical basis of this position, the majority believes that a general goal relating to the likelihood of core damage is both necessary and desirable.

There is some concern that increased safety goals will inevitably be accompanied by higher capital and operating costs. After some debate, it is concluded that lower core damage frequency does not necessarily lead to higher costs. In fact, a focus on economics could result in new approaches that simplify the design and operation.

Demonstration of No Severe Core Damage

Generation IV reactors must demonstrate that severe core damage will not occur for any plausible initiating event. This demonstration must be accomplished through integrated reactor testing.

This goal stems from the belief that the members of the public, regulatory bodies, investors, and operators will be far more convinced of the safety and reliability of a plant that has physically demonstrated the ability to cope with upsets than for one whose safety and reliability is demonstrated primarily by engineering analysis. The thrust of this goal is demonstration of the reactor's ability to successfully respond to a broad range of potential initiating events without the occurrence of appreciable core damage. In this context, the term *initiating events* represents operational upsets that require a shutdown of the fission process and subsequent response of plant safety systems to remove decay heat and perform other safety functions.

This goal raises a number of questions for which specific answers are not fully developed. Among these are issues about what range of initiators should require testing, whether or not the demonstration should be extended to include initiators and safety system failures, how to ensure safety for events that are impractical to demonstrate, and so forth. This goal needs to be more fully developed for each specific Generation IV system concept. However, the fundamental driver for this goal is clear. It is the relative certainty and satisfaction that comes from being shown, rather than told, that a design is physically able to cope with a broad range of severe challenges without incurring appreciable damage.

A number of practical difficulties exist with respect to this goal. Among these are definition of the kinds of tests that would satisfy the overall objective of this goal and evaluation of the safety of the tests themselves. It is recognized that while this goal is appealing in its simplicity, practical difficulties may prove this goal to be simplistic. Some are concerned that this goal could be prohibitively expensive. However, it is believed the goal is justified by the fact that testing would not involve damage to a successful design. Thus, in this goal, safety demonstration is more akin to operational acceptance testing than to destructive testing. In short, while the costs of unsuccessful testing could be prohibitive, the costs of successful testing are not.

No Need for Offsite Response

No credible scenario should exist for release of radioactivity requiring offsite response to ensure public safety.

The intent of this goal is that the probability should be extremely low of any accidental offsite release of radiation that might cause measurable health consequences. This goal is not to be construed as *zero probability of any accidental release*, which is held to be both unattainable and unnecessary. Rather, the focus of this goal is to eliminate the need for formal emergency planning.

The general consensus is that this goal must address the fact that Generation IV reactors should introduce essentially no increased risk to the public as a result of any credible accident scenario. In discussing the way to express this goal, some offer that there should be "no radiation release beyond the containment from any anticipated accident." Others suggest challenging the linear, no-threshold dose model and allow for the possibility of accidental releases up to levels that would be more clearly associated with measurable health consequences.

It is offered that *offsite response* can best be defined in terms of the current U.S. protective action guideline limits. Thus, a reasonable measure of this goal could be expressed as "no credible accident scenarios that could result in offsite releases of radiation exceeding U.S. protective action guidelines." It is understood that these guidelines may change as improved radiation dose-response models are developed. Also, other countries may choose to adopt other action thresholds, which would then become the measure of this goal in their country.

ALARA Radiation Exposure

Generation IV reactor designs must afford ALARA radiation exposure over the total system lifetime.

Safety must be an integral part of all aspects of the Generation IV system, not just the reactor. Front-end fuel cycle processing, plant operation and maintenance, plant decommissioning, and eventual waste handling and disposal issues all must be evaluated for safety. This goal represents a general consensus that a broad range of issues must be considered.

The intent of the goal is that personnel exposure to radiation must be minimized with respect to the full set of plant operations and the reactor fuel cycle. It is recommended that this goal be evaluated to current occupational exposure limits and continued adherence to the general concept that exposures should be as low as reasonably achievable (ALARA). Future research may show current occupational limits to be lower than necessary, and these limits might be raised in the future and afford lower costs without sacrificing personnel safety.

Tolerant of Human Error

Generation IV reactors must be highly tolerant of human error.

This goal stems from the general observation that a very large number of accident precursors and reportable events that occur worldwide in currently operating nuclear power plants involve human errors. Probabilistic risk assessments of operating plants consistently show human errors to be among the dominant contributors to nuclear power plant risk. Based on this observation, Generation IV reactors must be highly tolerant of human error.

It is clear that the implications of this goal potentially include consideration of design elements that maintain safety margin, equipment status monitoring, use of advanced automation for process monitoring and control, advanced displays as operator aids, and expert systems to provide cues for operating procedures. Also, with respect to this goal, the nature of accident processes that are possible in Generation IV reactors should not include any accident sequences that would require quick or complex operator responses. Some express that the ideal state with regard to this goal would be a reactor design that requires no operator intervention to mitigate any plausible accident conditions. The operators would serve only to monitor and back up automated responses to off-normal reactor events.

The dual nature of operator performance with respect to potential accidents is an important consideration. The dual nature arises from the fact that nuclear power plant operators have the potential to initiate or exacerbate accident sequences, while they also have the capability to creatively respond to accident conditions in a way that terminates accident progression before damage is done or mitigates the effects of the accident sequence. One of the challenges for Generation IV reactor designs is to minimize the potential for operator errors that contribute to the potential for nuclear power plant accidents, while retaining the ability of the operator to positively intervene when necessary.

Solutions for All Waste Streams

Generation IV systems must have complete waste solutions for all waste streams.

It is important that complete processes and disposal paths for Generation IV waste streams be identified prior to operation of any Generation IV prototype. Continued development of any Generation IV energy system should be tied to responsible resolution of questions regarding waste disposal. This goal encompasses all waste streams in Generation IV systems, including tailings from mining and enrichment plants, radioactive waste from processing and operations, low-level waste, contaminated and/or activated structures, and nonradioactive hazardous waste.

Although several alternative technical approaches may be suitable for disposal of Generation IV wastes, those finally deployed will be compatible with the goals for the overall energy system. For example, goals for proliferation resistance might preclude certain technologies for actinide recycle, which might be an effective waste minimization measure. Safety goals in some nations might prevent shipment of certain types of materials, thereby precluding certain waste management techniques. Overall, it is recognized that economic and socio-political considerations will have substantial influence over choices for waste management, and that waste management decisions will be made within the context of the overall system.

It is not yet clear whether spent fuel is to be regarded as a waste stream. Many in the community believe that spent fuel should be managed as an asset. Some even argue that all byproducts of Generation IV systems, from materials to residual heat, should become sources of benefit, and that R&D to develop technologies for beneficial use of all byproducts should be part of the system development. Economic considerations of the systems and government investments in R&D may limit the degree to which byproduct utilization can be implemented, and policy decisions regarding reprocessing or separation of weapons-usable materials may limit derivation of useful products from spent fuel.

Decontamination and decommissioning (D&D) of nuclear power plants is expected to result in wastes that require safe disposal. Although the participants preferred to not address D&D-related waste concerns in a goal, the consensus believes that D&D should be considered in developing and designing Generation IV systems to ensure that D&D-related waste can be managed effectively.

Public Acceptance of Waste Solutions

Politically and publicly acceptable solutions must exist for all nuclear waste streams and an implemented solution must exist for wastes from previous and existing plants.

Many in the nuclear technology community observe that current concerns over the disposal of radioactive waste are socio-political in nature, rather than technical. Although technical solutions to the disposal of many waste streams have been or could be developed, experience has shown that technically valid solutions are not always publicly accepted. In societies where public acceptance is crucial to the startup of operations with even minimal environmental impact, public and political opinion regarding methods of waste management must be addressed. In addition to public confidence, the confidence of prospective nuclear plant investors and operators will be essential if nuclear energy is to contribute to future energy needs. Investor confidence will require public acceptance of Generation IV systems and their waste management strategy. Therefore, solutions to Generation IV waste streams must be comprehensive and technically defensible, and achieve public confidence.

Establishing public confidence in the proposed waste management strategy for a Generation IV system may require that waste disposal for high-level nuclear waste from previous and existing nuclear power plants be successfully underway. In the United States and in many other nations for which repository disposal of high-level wastes is the chosen method, this means that the repository should be licensed, operational, actively receiving, and emplacing previously generated waste at the time Generation IV systems are being deployed. While it is recognized that programs to develop Generation IV systems will not likely include efforts to address waste from existing nuclear power plants, many believe this to be an essential condition for deploying Generation IV plants. Others believe it to be desirable but not essential.

Minimal Waste

Generation IV systems must minimize waste to the extent practical.

Some nations place high value on minimizing radioactive waste generated from nuclear energy systems. In fact, for several nations, waste minimization is an explicit objective of their nuclear energy development programs. On the other hand, many in the technical community believe that this is less important in the United States, where the difficulties in disposing of nuclear waste are related more to the radioactive or chemical hazards of the waste than to its volume. Although nuclear energy produces substantially less waste per unit of energy than many other energy supplies, there is considerably more expense in dealing with a given volume of radioactive waste than there is in dealing with nonradioactive waste. Therefore, economic incentive exists for some degree of radioactive waste minimization. Beyond this point, socio-political considerations in some regions or countries may also motivate waste minimization, despite an unfavorable effect on the economics. Decontamination and decommissioning should be considered through the development and design of Generation IV systems to ensure that D&D-related wastes can be managed effectively.

Minimal Attractiveness to Potential Weapons Proliferators

Development of Generation IV systems should preserve the current regime, where the misuse of the civilian nuclear fuel cycle is the least attractive route to potential weapons proliferators. This applies to both indigenous facilities and to exported components of the fuel cycle.

Civilian nuclear power has never been an attractive vehicle for proliferating weapons-usable materials. It should be more difficult for a weapons proliferator to use a Generation IV fuel cycle to acquire weapons-usable nuclear materials than is now the case with existing civilian systems. The level of difficulty will be increased by combining intrinsic and extrinsic features. Examples of intrinsic features are (1) reducing the inventory of weapons-usable material outside the reactor, (2) making weapons usable material inaccessible, (3) reducing the attractiveness of materials in the fresh and spent fuel and in the process streams, and (4) designing facilities and processes to minimize opportunities for misuse or diversion, to increase transparency, and to facilitate the interface with safeguards. Extrinsic features will essentially rely on improved safeguards technologies and procedures.

Intrinsic and Extrinsic Proliferation Resistance

Generation IV system design should rely on intrinsic proliferation resistance features to the maximum extent possible. Extrinsic barriers should complement them in a manner tailored to the specific fuel cycle.

The proliferation resistance of the future nuclear system will be the sum of contributions made by intrinsic and extrinsic features. Intrinsic features are generally believed to be more attractive and more difficult to overcome. Nevertheless, certain proposed intrinsic features of future fuel cycles might negatively affect the economics or even the safety of the system. In that case, extrinsic features that have been demonstrated to be effective should be employed. Furthermore, the adoption of new technologies might both reduce their cost and increase their effectiveness.

The proliferation resistance of the entire fuel cycle must be considered when assessing future systems; rather than seeking to optimize specific components separately, the entire fuel cycle (mining, enrichment, fabrication, irradiation, recycling, and final disposal) must be optimized simultaneously. This task will be made difficult by geopolitical factors and the need to take into account geological time scales.

Furthermore, proliferation resistance must be addressed without compromising other key attributes of the system, such as economics, safety, and waste. Thus, a global framework for simultaneously addressing these issues should be developed.

Evaluation of Proliferation Resistance

Generation IV designs must be evaluated for proliferation resistance relative to established guidelines.

While the concept and objectives of proliferation resistance are well understood, there is no established means to assess the relative proliferation resistance of a given system design. This might become a significant difficulty for designers of advanced systems who are trying to decide among several different approaches. Thus, for the successful design of Generation IV systems, it is necessary to develop and use a process or methodology by which proposed designs can be evaluated relative to an established guideline. It is also recommended that this process be developed in a general framework where proliferation resistance, safety, economics, and waste issues can be assessed simultaneously in order to resolve potential conflicts between them.

In order for system designers to proceed, a reference baseline for assessing inherent barriers to production, diversion, and theft of weapons-useable nuclear materials should be established. While it should be sufficient to make proposed fuel cycles less attractive to proliferators than dedicated production means, there is also strong belief that developing systems perceived as less proliferation resistant than existing fuel cycles would run into significant political roadblocks and would ultimately not be acceptable. Thus, a possible reference baseline could be derived from existing systems currently in operation. However, recognizing that the perception of proliferation issues is not the same for the United States and other nations, it may not be possible to establish a single baseline.

Potential Characteristics of Generation IV Nuclear Power Systems

The participants identified and discussed many possible characteristics that could enable Generation IV systems to meet the goals. While a large number of characteristics are listed below, most participants believe there was insufficient time to fully discuss the set and prepare it for recommendation to DOE.

1. The plant is designed to deliver a maximum amount of useful energy.
2. Plant availability factor is greater than 95%.
3. The plant capacity factor is optimized, which is expected to be somewhere in a range near 90%.
4. Operations and maintenance (O&M) costs continue to be less than 1 cent/kWh.
5. The plant maximizes the use of online maintenance practices.
6. The plant minimizes O&M labor, including both full-time and contract labor.
7. The system has minimized the costs relating to infrastructure in the country or region in which it is deployed.
8. The plant is designed for life extension through cost effective replacement of components and subsystems.
9. The plant minimizes refueling outage time.
10. The system considers the use of alternate fuel cycles in its design, to afford it flexibility in long-term operation.
11. Components and subsystems are mass-produced, and there is a high degree of standardization.
12. Inherent characteristics are used extensively to achieve safety functions. Processes and systems important to safety rely extensively on natural phenomena such as natural circulation, gravity, materials properties, etc.
13. The design eliminates potential for prompt criticality accidents.
14. The plant is capable of maintaining all safety functions in response to all credible external events, particularly severe seismic events.
15. Probabilistic risk assessment identifies design features that are important to safety.
16. Design and licensing is based on risk-informed principles.
17. Improved analytical methods are used to define and validate safety margins.
18. The plant has reduced dependence on complex human actions and elimination of accident scenarios that would require quick operator responses.
19. The plant has extensive use of expert systems, digital instrumentation and control, and computer-aided controls.
20. The plant has components and systems that employ advanced instrumentation and other technology to make them self-testing and self-monitoring.
21. The plant uses on-line monitoring of system status and degradation.
22. The plant has a simple, well-designed control room.
23. The plant makes optimal use of information technology.
24. The plant design incorporates high reliability of components and system.
25. The plant is designed to simplify operating procedures, maintenance procedures, and repairs.
26. Provision for onsite spent fuel storage is incorporated into plant design.

27. New waste management strategies include international repositories and international guidelines or standards for repositories and disposal practices.
28. Spent fuel is stored as a resource for later reuse or recycle.
29. The system waste management scheme incorporates any of several advanced technologies, including actinide partitioning and transmutation; partitioning of spent fuel waste into low-level, medium-level, and high-level streams; recovery and transmutation of long-lived fission products; and actinide recycle.
30. Chemically stable waste or fuel forms are employed to reduce the probability of radionuclide release from a geologic repository.
31. The plant has an up-front plan for decommissioning and handling of its discharged spent fuel.
32. The plant improves fuel utilization over the current once-through fuel cycle through use of higher fuel burnup to increase energy obtained from a fuel handling unit, or higher conversion rates to increase energy obtained per unit of uranium.
33. All waste streams are investigated as potential sources of ancillary value; e.g., as sources of isotopes or as irradiation sources.
34. The system makes all weapons-usable material highly unattractive and inaccessible.
35. The system design minimizes the attractiveness of materials to proliferators, for example, by relying on alternate fuel forms and incomplete separations.
36. The system reduces the inventory of weapons-usable material outside the reactor.
37. The facilities and processes are designed to minimize opportunities for misuse or diversion of weapons usable materials, and to facilitate safeguards.

The Path Forward for a Generation IV Program

To define the technical challenges involved in pursuing Generation IV, the DOE plans to develop a technology roadmap to guide its Generation IV efforts. DOE encourages other countries to do the same and then pool their findings and coordinate their subsequent activities. The DOE roadmap will be undertaken in FY 2001.

Generation IV Roadmap Activities

Although the details of the DOE roadmapping process have yet to be determined, it will likely involve the following activities:

- An initial survey of the state of development of a broad portfolio of relevant technologies and nuclear power system concepts throughout the world.
- Identification and exploration of the scientific and technical issues that must be resolved for each of the nuclear power system concepts considered in the roadmap. This is essentially a top-down examination of the concepts against the goals for Generation IV nuclear power systems. This document represents a first step toward establishing those goals.

- Identification and forecasting of the technologies that will enable the candidate nuclear power system concepts to meet the goals. This is essentially a bottom-up examination of the needed technologies.
- Development of recommendations for a technology-driven program to address the gaps identified between the top-down and bottom-up analyses. These recommendations will include feasibility studies to address critical technology issues that could become *showstoppers* for the various concepts. These feasibility studies will be initiated in FY 2001 as an integral part of the roadmap process and will begin to address issues relating to development and potential deployment of the various concepts.
- Identification of opportunities for possible international collaborative research efforts.
- Identification of institutional challenges facing a Generation IV program, including a discussion of nuclear R&D infrastructure capabilities and needs, and the regulatory and licensing aspects of advanced Generation IV nuclear power systems in a global context.

The research called for in the roadmap would enable selection of one or more promising Generation IV system concepts for further development. The current DOE Draft Strategic Plan projects that this could happen as early as FY 2005.[7]

In January 2000, DOE convened an international group of senior government representatives from nine countries to begin discussion of potential international collaboration for developing Generation IV nuclear power systems. This group issued a joint statement supporting research on next-generation nuclear power systems[8] and decided to form a senior technical expert working group to explore areas of mutual technical interest. They will make recommendations regarding both research and technical development areas to be explored and the process by which the collaboration should be achieved. The first meeting of their technical experts group was held in April 2000. The results of the international group discussions will be input to the Generation IV nuclear power systems technology roadmap.

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7 Department of Energy, "Draft Strategic Plan – Strength through Science: Powering the 21st Century," available at www.cfo.doe.gov/stratmgt/plan/doedraftsp.pdf, February 18, 2000, p. 30.

8 "Joint Statement on Generation IV Nuclear Power Systems," available at www.ne.doe.gov/jointstatement.html, February 10, 2000.

Interrelationships with Other Key Activities and Programs

DOE has initiated or planned several programs and activities relevant to the Generation IV initiative. These activities will both feed into the development of the technology roadmap and be influenced by the outcome of the roadmapping effort:

- ***Nuclear Energy Research Advisory Committee (NERAC).*** NERAC has convened several subcommittees whose work has an important relationship to Generation IV:

  A first NERAC subcommittee is engaged in an effort to develop a Long-Term R&D Plan for the DOE Office of Nuclear Energy. This plan is being developed with input from a broad spectrum of academic, industry, national laboratory, and other participants, including both advocates and critics of nuclear power. The plan will contain specific recommendations regarding the research focus areas that should be included in the Generation IV Roadmap.

  A second NERAC subcommittee on Technology Opportunities for Improving the Proliferation-Resistance of Nuclear Power Systems (TOPS) is developing recommendations to DOE on areas of research to improve the proliferation resistance of current and future reactor technologies and nuclear fuel cycles. The TOPS recommendations will also be a key input, guiding the proliferation-resistance R&D included in the Generation IV Roadmap.

  Finally, a third NERAC subcommittee is engaged in developing recommendations on U.S. nuclear technology R&D facility infrastructure. The results of their report will constitute the primary input to the discussion of research facility capabilities and needs in the Generation IV Roadmap.

- ***Ongoing Research Programs.*** In developing the Generation IV Roadmap, DOE will survey relevant research being conducted in the United States and abroad and factor appropriate information into the roadmap. This survey will include programs such as NERI, Accelerator Transmutation of Waste, Nuclear Energy Plant Optimization, Nuclear Engineering Education Research, the proposed International NERI (I-NERI) program, U.S. and Russian Plutonium Disposition and Proliferation Resistant Nuclear Technology programs, and other activities.

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Workshop Process

The Generation IV Workshop was held in Bethesda, Maryland on May 1-3, 2000. Nearly 100 experts and decision-makers from industry, national laboratories, academia, government, and world organizations participated. Over one-fourth of the participants were from outside the United States. The purpose of the Workshop was to discuss the desired goals and characteristics for Generation IV nuclear power systems. The objective of the Workshop was to recommend goals to DOE for Generation IV nuclear power systems that will offer a viable future nuclear energy option for the United States and the developed and developing countries of the world.

The Generation IV Workshop was organized by the two DOE NE Lead Laboratories for Nuclear Reactor Technology — the Idaho National Engineering and Environmental Laboratory (INEEL) and Argonne National Laboratory (ANL).

In preparation for the Workshop, a questionnaire was distributed to the participants. Over one-half of the questionnaires were returned, which gave an initial sense of the participants on the goals and characteristics. In order to best facilitate the large group, the discussion of goals and characteristics was divided into breakout groups on Economics, Safety, Waste, and Proliferation Resistance. A technical advisor was assigned to each breakout group, who served to summarize the questionnaires on each breakout topic. The technical advisors were

Economics	Dr. Ralph G. Bennett Director, Advanced Nuclear Energy, INEEL
Safety	Mr. Timothy J. Leahy Department Manager, Risk and Reliability, INEEL
Waste	Dr. Douglas C. Crawford Department Manager, Fuels Technology, ANL
Proliferation	Dr. Phillip J. Finck Associate Director, Technology Development, ANL

At the Workshop, the group assembled in a plenary session and heard speakers from the DOE, NERAC, industry, and the organizers. The participants then broke into the four topic areas for the next day and a half. In the breakout groups, the participants began with the summaries of their respective goals and characteristics, refining and editing them. Each group was assisted by a facilitator who kept the discussion flowing, a technographer who captured the edits and comments for all to see on a large computer display, and the technical advisor who sought to clarify elements of the discussion. In recognition of the interdependence of goals between the four topic areas, each of the groups was given a chance to present their intermediate results to the other groups and to comment on issues and conflicts between the groups.

To conclude the Workshop, the technical advisors gave a plenary session summary of each topic area. Following the Workshop, the technical advisors prepared a written summary and posted it on the Workshop website for a two-week comment period. Comments were incorporated to reach the final document, which was transmitted to DOE NE for consideration.

Mr. Magwood, DOE NE Director addresses the participants to close the Generation IV Workshop.