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NUCLEAR ENERGY: PRESENT TECHNOLOGY, SAFETY, AND FUTURE RESEARCH DIRECTIONS: A STATUS REPORT

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Preamble

In 1993, as the Clinton administration was settling in, the council of the American Physical Society took a position on nuclear energy, which included the following:

"A balanced energy policy…requires...strong programs to keep the nuclear energy option open, through: (a) the continued development of nuclear reactors which can be built, operated, and eventually decommissioned in a manner which is simple, safe, environmentally sound and cost-effective, (b) the development and implementation of programs for the safe disposal of spent fuel and radioactive waste, and (c) the development of an effective public education program to allow a more informed debate on the strengths and weakness of nuclear power."[1]

The current Bush administration now has issued an energy plan that endorses nuclear power[2]. This paper, written by experts in several areas, discusses the current status of topics directly related to that 1993 APS position.

I. Background

The beginning of the 21st Century marks a critical time for nuclear energy, arguably one of the defining technologies of the 20th Century. In the United States, the commercial nuclear energy era began with the U. S. Navy program directed by Hyman Rickover. Beginning with tests in 1953, this program not only initiated the nuclear power industry, but in many ways also set the tone for the industry for many decades. The first commercial nuclear energy plant, a 60 MWe pressurized light water reactor, was built in Shippingport, Pennsylvania, at the end of 1957,

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[1] APS Statement 93.7, Statement on Nuclear Energy, 21 November 1993.
[2] *National Energy Policy: Report of the National Energy Policy Development Group*, May 2001.

under Rickover's direction. Currently, 438 nuclear power plants are operating worldwide, with 103 operating in the United States. Nuclear energy provides 20% of U. S. electricity, and roughly 17% worldwide.

The initial wave of nuclear power plant construction in the United States, from 1960 – 1980, was followed by a period of re-evaluation of the economics of nuclear plants, questions on the safety of the entire nuclear fuel cycle, changing requirements for plant operation and staffing, and diverse public discussions of nuclear energy. This re-evaluation was driven by several factors, primarily (1) the sharp drop in electricity demand growth as a result of the oil shocks of the early 1970's and the subsequent emphasis on energy conservation and efficiency and (2) the 1979 accident at the Three Mile Island (TMI) nuclear plant.

The demand for energy – seen as virtually limitless in the 1950s and 1960s – as well as the price spikes and volatility of the 1970s and early 1980s drove development of nuclear energy. Prior to 1963 the largest nuclear plant built was 300 MWe, while the mean reactor size just a few years later, in 1965, was 660 MWe, and was over 1,000 MWe in 1970. The rapidity of this increase – similar to that seen in fossil-fuel plants during that time -- meant that research and development could not keep pace with the changing needs of the industry, including the large number of orders. A significant amount of testing and engineering to meet the demand was done as part of the design process, resulting in new plant construction that did not utilize the experience that could have been – and would have been expected – to have been gained from the growth of the industry. This pattern of "build and learn" was not confined to nuclear plants alone.

Considerations of nuclear power involve four difficult issues: economics, waste disposal, safety, and proliferation. In the United States, nuclear plants have taken much longer to build than in countries such as France and, especially, Japan, and have cost far more. Construction costs of new U.S. plants rose to several billion dollars, and construction times stretched to over a decade. Unlike the French program, U.S. plants have usually been "one-of-a-kind". While Japanese plants are of several types, the variety is far less than that in the U.S. The resulting costs and uncertainties of completion led to cancellation of existing U.S. orders and no new orders being placed since the late1970's. In addition, in the 1970's and early 1980's, U.S. capacity factors (the percentage of time the plant is generating electricity) were less than 70%. Combined, the economics of nuclear plants led many observers, including utility executives, to conclude that U.S. nuclear plants would be shut down before their 40-year licenses would be reached.

(A periodically contentious issue is the Price-Anderson Act, recently re-authorized to extend to 2017. Under this Act, total liability for a nuclear accident is limited, although certain usual requirements of proof of cause are waived. Originally proposed as a means of encouraging a new industry, the Price-Anderson provisions have long been seen as a major federal subsidy by the Act's critics. The total amount committed has continued to rise, since each plant is required to provide an amount. The current coverage is $9.5 billion from the nuclear industry, after which Congress would decide how to cover additional costs. Although the first few reauthorizations were heavily debated, the more recent ones have not been heated.)

However, while no new plants have been ordered in the U.S., the situation for operating plants has improved dramatically. Based upon strict attention to operations, capacity factors of US plants have risen to become among the world leaders, with the average getting close to 90%. Nuclear plants that only a few years ago were set to be sold for not much more than the price of the fresh nuclear fuel owned by the company, have now been retained by their parent companies, or sold for dramatically higher sums. In addition, the number of plants for which license extension (providing an additional 20 years of operation) has been requested continues to rise. The Nuclear Regulatory Commission (NRC) expects at least three-quarters of operating U.S. plants to apply for such extensions.

The spent (used) fuel from a nuclear reactor contains highly radioactive materials, requiring the fuel to be carefully shielded for many centuries. Currently, in the United States the spent fuel is stored at the reactor sites, but is to be sent to a geologic repository to be developed by the Department of Energy (DOE). DOE is decades behind the legislated schedule to develop such a repository or to take the fuel from the utilities. The lack of a developed endpoint for the fuel lessens the support of some utility planners, generates questions in state public utility commissions, and makes expansion of nuclear power less attractive.

Although US industry, under pressure from both Congress and the NRC, responded to the TMI accident by developing industry-wide improvements and continued emphasis on safety, concerns remain. The accident at the Chernobyl reactor in the Ukraine in 1986 heightened such concerns, although both the reactor and the causes of the accident are not connected to US designs and operations. US and developed world reactors have had an excellent safety record after TMI. Nevertheless, because of the energy in the reactor and the amount of radioactive materials present, safety concerns will continue to be an issue unless totally new concepts can be developed. The recent finding of circumferential cracks on nozzles at some US plants demonstrates that all is not understood about reactor safety.

Proliferation concerns relate to the presence of nuclear weapons-usable plutonium in reactor spent fuel, the potential to separate such plutonium in reprocessing facilities, and the possibility of concealing a nuclear weapons program within a nuclear power program. The IAEA safeguards inspection system was established to call international attention to countries attempting to develop nuclear weapons. Several international organizations and agreements seek to constrain such attempts. Attempts to traffic in weapons-grade nuclear materials and expertise have originated in Central European and former Soviet nuclear facilities.

Recent attention to the environmental effects of fossil-fuel use – including global warming and local air quality – has rekindled interest in the prospects for expanding the nuclear industry. Support for this re-invigoration of the nuclear industry has come from the highest political circles in the current Administration, with Vice President Cheney saying that:

> If you're really concerned about global warming and carbon dioxide emissions, then we need to … aggressively pursue the use of nuclear power, which we can do safely and sanely, but for 20-some years now has been a big no-no politically.

Vice President Cheney also directed the National Energy Policy Project to make this same recommendation. A number of similar statements have emerged, some envisioning a future with one-third or more of total electricity coming from nuclear power (Sailor, *et al*, 2000). The U. S.

Department of Energy also is engaged in the 'Generation IV' study to plan the next anticipated wave of nuclear power plants, ones that would be less expensive both to build and to operate, and would rely on passive safety features.

The previous administration, essentially opposed to nuclear power, did recommend an expanded R&D program for nuclear energy. In a 1997 report, the President's Committee of Advisors on Science and Technology (PCAST) wrote:

> "We believe that the potential benefits of an expanded contribution from fission in helping address the carbon dioxide challenge warrant the modest research initiative proposed here, in order to find out whether and how improved technology could alleviate the concerns that cloud this energy option's future. To write off fission now as some have suggested, instead of trying to fix it where it is impaired would be imprudent in energy terms…."[3]
>
> "Nuclear power is a major factor in restraining the growth in emissions, and it will be more difficult for the United States to meet emission goals without nuclear power."[4]

It remains an open question whether the advances in nuclear power achieved over the last decade can be utilized to develop a nuclear fuel cycle that meets the proliferation concerns and provides the safety and economic advantages needed to develop support in the industry, among investors, and in the general public.

II. Aims of the Report

As energy issues return to the national policy debates, including issues associated with global warming, nuclear power also has begun to be discussed more vigorously than in the past twenty years. Safety concerns have been a major criticism of nuclear power. This paper reviews the methods used to analyze the safety of reactors and presents a description of the new designs. The issues of radioactive waste and security also are reviewed. The Department of Energy's long-range program is described and possible research areas are presented.

III. Methodologies to analyze safety

A.   <u>Overview of the general approach used to achieve high levels of safety in reactor design and operation</u>

[3] "Federal Energy Research and Development for the Challenges of the Twenty-First Century", Report of the Energy Research and Development Panel, The President's Committee of Advisors on Science and Technology, November 1997, p. ES-5.
[4] *Ibid.*, p. 5-21.

There is a broad international consensus within the reactor-safety community concerning the key elements that are necessary in the design and operation of a nuclear power reactor to achieve a very high level of safety. While the presence of these key elements generally should provide a high level of safety, the absence of one or more of them is always a cause for concern. Here the phrase "a high level of safety" means a very low probability of an accident that might cause death or injury to offsite populations due to radioactivity, or might cause important contamination of offsite land and property. It also implies that the risk to onsite workers and the risk of damage to the facility itself are of acceptably low probability, because the elements needed to achieve these are very much congruent with the elements needed to protect offsite populations and property.

Before describing the major elements needed to accomplish reactor safety, it is important to describe in broad terms the safety-engineering challenge. Simply stated, for a reactor to be acceptably safe it is necessary to assure under all potential upset conditions (a) that the nuclear chain reaction can be shut down and maintained in a shutdown condition (known as the "reactivity control" function) and (b) that the thermal energy (heat) in the reactor, both heat present at the onset of the upset and heat generated by the continuing radioactive decay processes in the core, is removed to a safe ultimate heat sink (known as the "heat removal" function). If both of these can be accomplished in an accident, the radioactivity within the reactor can be contained; if they cannot, it will not be. While other crucial functions, such as the containment function and the emergency-protective-action function, need to be accomplished as back-ups in case these vital functions fail, the most important aspects of preventing harm from the radioactivity are the functions of reactivity control and heat removal.

Different reactor designs accomplish these vital safety functions in different ways. It is broadly accepted that a design is preferable – that is, it is generally "safer" or, at least, more "demonstrably safe" – to the extent that each of these functions is accomplished by relying more on physical principles and passive features and less on active equipment and human intervention. This does not mean that a reactor design relying mainly on active equipment and human intervention cannot be made acceptably safe, but it does mean that there is a broadly accepted hierarchy in which designs incorporating physical principles and passive features to accomplish the vital safety features generally are preferred.

A number of quite new reactor designs are now under active development. A number of important designs that offer incremental advances also are being pursued. Many of them claim as explicit advantages that they rely more on physical principles and passive features to accomplish the key safety functions. Some of the new designs rely on small size to help accomplish the functions passively. (For example, a reactor can be made small enough so that it can "cool itself" passively without active systems, although most such small reactor systems are impractical or uneconomic.) Other designs embed highly reliable and redundant/diverse means to accomplish the major safety functions.

The key elements that are necessary in the design and operation of a nuclear power reactor to achieve a very high level of safety are the following:

a) A strong base of both scientific and engineering knowledge to support each aspect of the reactor-safety program outlined below.

b) A reactor design that accounts for all important potential accident scenarios by employing systems and operational features that reduce the probability of each such scenario, or reduce its potential consequences (or both) to acceptable levels; and the ability to analyze that design well enough to provide high assurance that the above is achieved.

c) A reactor design that utilizes established codes and standards and incorporates adequate margins to assure acceptable performance in light of the uncertainties in knowledge.

d) A reactor design that incorporates a defense-in-depth safety philosophy to maintain multiple barriers, including both physical and procedural barriers as appropriate.

e) A reactor design that uses a philosophy of redundant and diverse safety systems to assure highly reliable performance during all potential accident scenarios.

f) A reactor design that incorporates technical specifications that conservatively define, control, and circumscribe a safe operating envelope.

g) An adequate basis, in experiment, theory, and testing, to support the design specifications and the safety analyses used for safety assurance.

h) The use of quality materials, quality manufacturing of equipment, and quality construction and maintenance practices.

i) An operating philosophy that embodies a profound respect for the possible dangers inherent in reactor operations.

j) A staff of qualified operating and maintenance personnel, supported by a management committed to a strong organizational safety culture, and also supported by a strong engineering capability.

k) An ability to analyze the safety achieved by the operation, in terms of both realistic probabilistic analyses and conservative engineering analyses of the as-built-as-operated facility; and an ability to use the information from such analyses to maintain and enhance safety.

l) Emergency plans that adequately protect offsite populations.

m) An operational safety culture that is both comprehensive and managed properly, and that incorporates an effective self-assessment and corrective-action program.

n) A system that derives safety insights from operating experience and from analyses performed both within the reactor organization itself and elsewhere around the world, and that applies these insights effectively.

o) A strong management organization with both the resources and the motivation to maintain all of the above.

p) An arrangement that has access to a continuing program of nuclear safety research, and that utilizes the insights derived from that research for safety improvement.

q) An independent regulatory authority that is responsible to the government and the public for overseeing safety, and for taking corrective or enforcement actions as necessary.

Over the past thirty years, international operating experience has demonstrated the importance of high-quality engineering of the facility and high-quality human performance. In the latter arena, operator qualifications and training must be supplemented by operating procedures for both normal and abnormal/emergency situations, and by procedures for accident mitigation. All of the above must be embedded in a strong safety culture, to ensure that each element of the entire safety envelope is maintained. Said another way, the basic safety values and attitudes of the operating entity, from top to bottom, can be as important as the basic design --- inadequacies in either can lead to a degradation of safety.

Many countries deploy nuclear power reactors that achieve very high safety levels because all of the elements above are present and are maintained. It is in this sense that the nuclear-engineering community believes that adequate safety levels have been achieved in these countries. The IAEA (International Atomic Energy Agency) has assisted in upgrading the conduct of operations in many of its member countries. However, in some countries significant gaps exist between what is known to be needed and what now exists. Major efforts are underway, with international assistance, to upgrade the performance of the reactor-safety systems in these countries.

B. Overview of methodologies used to assess the probability of accidents (severe and "moderate")

In the early days of reactor operation, the methods used to assess how well safety was achieved were qualitative rather than quantitative because no analytical methodology existed that could provide quantitative estimates of the risks. This also is true for many other complex technological endeavors (manned space travel is another example) where severe accidents are a concern but occur too rarely to provide an evidentiary basis for estimating the risks.

In the nuclear-power arena, a very capable methodology has evolved that now provides a strong technical basis for such safety assessments. This is the "probabilistic risk assessment" (PRA) methodology, which builds on the groundbreaking "Reactor Safety Study"[5] performed by a large group under N. Rasmussen of MIT in 1973-1975. The PRA methodology essentially involves writing down in the form of "event trees" each of the important accident sequences (from initiating event to core damage to radioactive release) that might result in a major accident, and then analyzing the likelihood of each sequence using logic, equipment reliability data, human reliability data, an understanding of the correlations among failures, an understanding of the physical phenomena in each scenario, and a wealth of design and operational information. Originally, the PRA methods were developed to deal with accidents initiated by internal equipment faults and human errors. Today the methods can also deal well with potential accidents initiated by internal fires, by external phenomena such as earthquakes and tornadoes, and by upset conditions occurring during shutdown conditions as well as at full power.

For analyzing the probabilities and consequences of power-reactor accidents, the methodology has reached a state of maturity in which it is now routinely used by both the operating entities and the safety regulators worldwide as a continuing check on how well each of the major elements of reactor safety is achieved.

However, the PRA methodology cannot provide highly accurate estimates of the probabilities and consequences of the major accidents of concern: some of the underlying data and models are not known well enough to support such a very accurate estimate. Hence the uncertainties in the "bottom-line" numbers for the annual core-damage frequency, or the likelihood of a specified large radioactive release of a certain size and character, are often as large as plus-or-minus an order of magnitude or more.

Therefore, the major use of the PRA methodology is not to produce such "bottom-line" assessments, important as they are in providing an overall understanding of the safety levels achieved. Rather, the principal applications of PRA are to enable the analyst and the safety decision-maker to understand which elements of the overall system contribute how much to safety, and why; and to study the effect on overall safety of changes in the system (be they undesired changes due to equipment failures or human errors, or planned changes such as scheduled maintenance that may temporarily compromise part of a safety function.)

It is important to emphasize that the methodology of PRA, which was originally developed to assess the overall probabilities and consequences of major undesired power-reactor accidents, does indeed provide such assessments and that these assessments are of broad use to policy-makers, despite the large numerical uncertainties in the bottom-line risk numbers. In most countries around the world these bottom-line risk numbers are judged acceptable by regulatory authorities, providing the context for the rest of the work that reactor-safety professionals do in maintaining and improving reactor safety.

Another major use of PRA methods is to assess the effectiveness of the overall design and operation, by highlighting where additional equipment or modified procedures can enhance safety. Also, PRA can identify where it would be feasible to relax strict

[5] Nuclear Regulatory Commission report WASH-1400.

engineering/maintenance standards for equipment that was originally thought to be "required for safety" using traditional engineering principles, but that in fact contributes little to safety; such relaxations can simplify operations or save on human or capital resources. PRA helps to establish optimum preventative maintenance programs by focusing on the risks associated with equipment/system failure. The application of PRA in maintenance, called "reliability-centered maintenance", identified cases where increased preventative maintenance was needed, as well as cases where relaxed preventative maintenance was appropriate. Another major use of PRA is to allow the regulatory authority to concentrate its own resources on those design or operational aspects that contribute most to the safety of a given reactor facility, for example by guiding regulatory inspectors about "where to look". PRA also can highlight areas where not as much is known as we would like – thus motivating development of new knowledge, either knowledge from operating experience or knowledge through advanced research.

It also is useful to recognize that, although PRA methods are mature enough to be used routinely, there are important areas where additional PRA-methodology research could be of benefit. These include our limited understanding of how to analyze and affect the role of safety culture and management as it influences reactor safety; our incomplete understanding of human performance under stress, including errors of commission and errors of cognition; our limited understanding of how certain correlations among failures may affect safety; and our need for more realistic models of the detailed behavior of radioactive materials inside the facility in some accident conditions. Further, the understanding of the effects on human health arising from potential reactor accidents is severely limited by the incomplete understanding of the dose-response relationship for radiation doses well below those that produce short-term clinical effects. Because of knowledge limitations, the reactor-safety-analysis community has always applied dose-response models more suited to radiation protection than to realistic assessment. All of these areas could benefit from the development of new knowledge or new analysis tools, or both, which is the purpose of reactor safety research.

IV. NEW DESIGNS

(a) <u>Advanced Light Water Reactor Designs</u>

Several advanced light water reactor (ALWR) designs have been developed in the past decade with the primary purpose of serving the future U.S. electric energy market but with recognition of an important and nearer term international market potential. All of the designs are based on the technology used in the 252 pressurized light water reactor (PWR) and 92 Boiling Water Reactor (BWR) commercial power plants in operation in the world today, representing 80% of the total world nuclear power capacity. They meet the established Nuclear Regulatory Commission (NRC) safety regulations as well as in-depth requirements stipulated by the prospective owner-operators of future nuclear plants.

The PWR and BWR are conceptually similar. The PWR design circulates water through the uranium-fueled reactor core, transferring the heated water to a steam generator, the steam from which rotates a turbine-generator to produce electricity. The BWR design circulates the water directly from the reactor core to the turbine, eliminating the need for the steam generator. Both types use slightly enriched uranium oxide fuel. Both have redundant safety instrumentation and emergency core cooling systems to minimize the chance of an accident that could cause damage to the reactor core. Both types, except for some in the former Soviet bloc, are enclosed in a steel or re-enforced concrete containment building to prevent leakage of radiation to the atmosphere in the event of a severe accident.

An important element of the overall development of these advanced systems was carried out under the auspices of the ALWR Program[6], a joint DOE and international nuclear industry and government effort. The Program established a set of owner operator requirements[7] to assure safety, reliability, and operability as a base for standardization, supported the design effort, and sponsored extensive confirmatory testing of the new design features.

The advanced LWR designs incorporate many improvements over the present fleet of LWRs operating in the U.S. These improvements have been derived from three primary sources:

- Application, through supporting R&D, of the extensive worldwide operating experience with LWRs to improve safety and component reliability and to increase operability.

- R&D carried out by the industry and the Nuclear Regulatory Commission (NRC) to apply the safety lessons learned from the Three Mile Island accident.

- Innovative R&D that showed ways to significantly simplify the plant designs.

Significant incremental improvements in safety, reliability, and operability came from the first and second sources. The first source was tapped through the formation of an international steering committee of utility executives with extensive experience on operating LWRs who, with the help of their staffs and the Institute for Nuclear Power Operations (INPO), identified the needed changes in design to incorporate the operational lessons learned in safety, reliability and operability. These changes are incorporated in ALWR requirements document.[8] The utility steering committee not only stipulated the changes but oversaw the implementation of them in the ALWR design wo85

[6] Santucci, et.al., “The Advanced Light Water Reactor Programme: an International Endeavor” Nuclear Energy Volume 36, No. 4, pp. 313-321, August 1997; “Nuclear Power: Technical and Institutional Options for the Future”, National Research Council, National Academy Press, Washington, DC, 1992; Taylor, J. J., “Improved and Safer Nuclear Power”, Science, Volume 244, pp 318-325, April 1989.

[7] “Advanced Light Water Reactor Utility Requirements, Vol. I, Rev 2, March 1999, Electric Power Research Institute, Palo Alto, CA

[8] *Ibid.*

rk. Many of these improvements have also been applicable to the U.S. fleet of operating plants, making a contribution to the increase in their average unit capability factor from 62.7% in 1980 to 91.1% in 2000, equivalent in capacity to more than twenty new large nuclear plants.

The second source was tapped from the NRC's TMI Action Plan, formulated after the accident to define the necessary changes in design to minimize the chances of another severe accident. The experience gained in implementing that Plan and the greater ease of effecting the changes in new, rather than back-fitted, designs was invaluable. A key analytical aid in the implementation process was the probabilistic risk assessment (PRA) methodology pioneered prior to TMI by Rasmussen, *et al.*, in the WASH 1400 report. That methodology was a major tool in the development of the ALWR designs and was a basic NRC requirement to obtain their design certifications.

The third source, innovative R&D, produced two major innovative improvements: (1) Plant designs with passive safety features (i.e., natural processes, such as gravity, natural circulation, condensation, evaporation, and compressed air) were utilized to provide emergency cooling of the reactor core and containment building instead of power operated pumps and their associated piping, valves, and controls. (2) Simplifications in design were devised from the use of the passive features and other innovations to reduce the plant materials and equipment content and make the plants easier to operate.

Nuclear plants are the second most capital-intensive electric generating plants in commercial use (the first being hydroelectric systems). Their economy is achieved by their low fuel cost and transportation logistics. The unusually low price and abundance of natural gas, however, have made gas-fired combustion systems more economical at this time. The emergence of a rate-deregulated market has erased investment incentive to build more expensive large base-load plants simply to provide diversity and robustness of supply. Further, proponents of nuclear power note that the environmental benefits of nuclear plants (no air pollution or global warming gas emissions) currently are given no economic credit. Thus, the cost-competitiveness of these designs in the U.S. rate de-regulated market is still problematical. Efforts are continuing to reduce the capital costs of nuclear power plants to make them economic without counting on increased gas prices, supply inadequacies, or the introduction of environmental credits.

Three advanced designs emerged from this overall effort and have been certified by the NRC: General Electric's Advanced Boiling Water Reactor (ABWR) built and operating successfully in Japan, Combustion Engineering's System 80+ PWR, which served as the design basis for plants under construction in South Korea, and Westinghouse's AP-600, a passive design certified by NRC. These three designs and the contemporary British Energy's Sizewell-B and EdF's N-Reactor PWRs, operating successfully in the UK and France, are summarized in the sections below.

(b) Advanced BWR (ABWR)

By 1977, eighteen General Electric Boiling Water Reactors (BWRs)were operating well in Japan. With continued nuclear plant growth projected, the Tokyo Electric Power Co. (TEPCO) asked General Electric, and Toshiba and Hitachi to develop an advanced design to improve on the cost, reliability, and safety of the BWR's then in operation. GE and its partners looked at the BWR designs around the world and examined those characteristics that led to problems, and the characteristics that added reliability and lower capital and generating costs. The positive designs were incorporated in the new ABWR, and the problem characteristics were eliminated, or minimized.

In 1985, a detailed review of the new design by GE concluded that the design had so many advances that it was too complicated to meet its reliability goal. GE, Toshiba, and Hitachi, made a presentation to TEPCO, recommending that the design should be simplified. The final design was completed in 1988, and a license to build the first ABWR was issued by the Japanese Ministry of International Trade and Industry (MITI) in 1991. Excavation of the site at Kashiwasaki -Kariwa, on the Western Shore of Japan, began in September of 1991. From first concrete laying, to the loading of fuel took just 36.5 months and, after many tests, the first plant went commercial in 1996. The second ABWR went commercial a year later. The total construction time from first concrete to commercial operation was 51 months. Both plants area rated at 1315 MWe.

A key feature of the ABWR is to place the reactor pumps inside the reactor vessel, which eliminates large circulation piping from the vessel and pipe vessel penetrations. Among other things, this reduces the size of the needed emergency core cooling system during postulated loss-of-coolant events, and therefore reduced the size of the containment building. In addition, the reactor vessel has extensive use of forged rings instead of welded plates. The ABWR Reactor building, including the containment, was configured to simplify and reduce the operation and maintenance requirements. Controls and instrumentation were enhanced through digital technologies with automated, self-diagnostic features. The human-machine interface was improved and simplified using advanced technologies such as large, flat panel displays, touch screen cathode ray tubes, and function-oriented keyboards. Many operating processes and procedures were automated.

All of the design goals have been met. Refueling outages have been kept to 55 days, the minimum allowed by regulation in Japan. Between outages the plants have operated at near 100% capacity. For the Kashiwazaki ABWR plant, the annual amount of radwaste has been 8 m^3 and total occupational exposure has been 30 man-rems per year.[9] Studies show that less than one unplanned scram[10] per year will be experienced with the ABWR, and increased system redundancies will permit on-line maintenance. The performances of

[9] These performance numbers compare with world experience as follows: average annual radwaste is 39 m^3 and average annual man -rem exposure is 126 man-rem. Data from email of 30 October from John Redding of GE. For US BWR plants, the median radwaste volume was 71 m^3 in 2000 and the median exposure was 150 man-rem in 2000. Data from World Association of Nuclear Power Operators (WANO) 2000 Performance Indicators.

[10] A scram is a sudden shutdown of the reactor.

both ABWR units have demonstrated their reliability with over four years of operating experience.

(c) Advanced PWRs Built or Under Construction

System 80+

System 80+ is a PWR of large unit power output, ranging from 900 to 1300 MWe. The System 80+ design is based on the PWR introduced into the U.S. market by Combustion Engineering (CE)[11], which comprises 12 of the 69 commercial PWRs that are operating in the U.S. today. The design is conceptually the same as the Westinghouse PWRs that have been deployed in the U.S. (49 of the 69) and overseas. These PWRs are distinguished from the third type of PWR deployed in the U.S. by B&W[12] principally in the utilization of recirculating, rather than once-through, steam generators.

Korea Electric Power Company (KEPCO) became convinced of the merits of the design through the successful operation of two predecessor System 80 units. This conviction, coupled with their in-country capability in the design, manufacture, and construction of the Combustion Engineering designs, has resulted in the System 80+ being selected as the design basis for South Korea's standardized nuclear plant for a planned major nuclear power expansion. Two 1000 MWe Korean Standard Nuclear Plants are under construction in South Korea which incorporate advanced design and safety features derived from the 80+ plant and are scheduled for commercial operation in 2002.

The System 80+ design is a substantial advance over the original CE design, incorporating safety and reliability features called for by owner-operators' requirements developed under the auspices of the ALWR Program. For example, the fuel thermal margins have been increased to ease the demands on the operator during upset conditions. The coolant temperature has been decreased to reduce corrosion deterioration in the major components. The calculated probability of the onset of a core destructive accident has been reduced by a factor of ten below that required by regulation. Modern digitally-based control and diagnostic systems have been provided. With those improvements and its proven technology and licensing base, the System 80+ design has been certified by the NRC.

Sizewell B

Sizewell B[13] is a 1250 MWe PWR based on the Westinghouse design deployed in the 70s in the U.S. As in the case of the other advanced LWRs, worldwide operating experience was utilized in up-dating the design for UK operation. The plant entered commercial operation in the UK in 1995, the only light-water-cooled nuclear plant among seven gas-

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[11] Recently, CE has merged into Westinghouse under the majority ownership of British Nuclear Fuel Limited (BNFL).

[12] Babcock & Wilcox, which no longer manufactures nuclear reactors.

[13] Power Reactor Information System (PRIS), IAEA, Vienna, Austria, www.org/worldatom

cooled commercial power units operating there. The British, working with Westinghouse, improved the Westinghouse design, providing an advanced and more redundant digital-based safety I&C system and stronger accident mitigation features. An advanced digital-based control room was included, utilizing state-of-the-art human factors engineering and on-line diagnostics. Additional redundancy and diversity was provided in the emergency core cooling system. The plant has achieved a good safety and reliability record.

Electricite de France (EdF) Designs

The most recent addition to French nuclear power capacity has been a new series of higher unit power output than the previous series of plants. Four units[14], Civaux 1, 2 and Chooz-B 1, 2 have been constructed, the most recent of which entered commercial operation in May 2000. All are power up-grades of the PWR Framatome/EdF designs that were based on the Westinghouse PWR, obtained through licensing agreements. They incorporate the operating experience of the French nuclear fleet as well as PWRs worldwide, incorporate modern digital-based control systems and improvements in safety and severe accident mitigation.

(d) Advanced LWRs In Design Phase

AP-600

The Westinghouse AP600[15] is a 610 MWe PWR with passive emergency core and containment cooling. Significant simplification has been achieved by eliminating the electrically powered emergency cooling systems. There are 60% fewer valves, 75% less piping, 80% less control cable, 35% fewer pumps, and 50% less seismic building volume than in present PWRs. The passive cooling systems also eliminate the need for active safety support systems, such as AC power, HVAC, cooling water, and the support network needed for safety-class diesel generators.

The use of passive safety features results in the re-classification of some active components and systems from safety to non-safety grade. A "Regulatory Treatment of Non-Safety Systems" process, incorporating both deterministic and probabilistic criteria and evaluations, has been defined to provide regulatory oversight for active non-safety related systems. The resulting reliability standards assure that the active non-safety systems will effectively minimize challenges to the passive safety systems.

The power train is conceptually identical to the present PWRs but has been made safer and more reliable through, for example, canned-rotor primary coolant pumps, improved materials and design of the steam generators, a larger pressurizer volume to provide more stable plant system responses to upset conditions, and an automatic depressurization

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[14] *Ibid.*

[15] Winters, J. W., "The AP-600: Design Certified and Ready to Build", Nuclear News, September 2000, American Nuclear Society, La Grange Park, IL

system that permits a controlled reactor coolant system pressure reduction under accident conditions.

The cost goals set for the AP-600 are estimated to have been met, but proved to be insufficient when abundant supplies of low cost natural gas became available in the 90s. The overnight capital cost[16] of an nth-of-a-kind AP-600 is estimated at $1,660/KWe, which would make it competitive with gas-fired electric generators if gas cost $5.00/million BTU. Spot prices of gas have equaled and exceeded this level in the past year but long-term contract prices are still well below that level, in the range of $3.00/million BTU. Work has continued to develop additional capital cost reductions of the AP-600 without compromising its safety, reliability, and performance.

AP-1000

Westinghouse has turned to economy-of-scale as an alternative approach to solving this cost issue and has designed a 1000 MWe version of the AP-600, the AP-1000, rated at 1090 MWe. This design is conceptually identical to the AP-600 but its overnight capital cost comes down to $1,040/KWe, which would be competitive with gas-fired and coal-fired systems at present long term gas price levels of $3.00/million Btu. The basic safety, reliability, and performance characteristics are retained and the supporting tests and analytical tools of the AP-600 are applicable but there is a reduction in fluid flow and temperature margins compared to the AP-600 to accommodate the higher power output. The design with these reduced margins still meets present NRC regulations and the margins are still larger than those in the operating U.S. PWRs. Therefore, Westinghouse intends to submit an application to the NRC for design certification of the AP-1000.

SBWR and ESBWR

A small unit power (600 MWe) advanced BWR design with passive safety features, called the SBWR[17], has been developed by GE under the ALWR program. In addition to the utilization of natural processes for emergency core and containment cooling, full power capability is obtained through natural circulation, permitting further simplification by removal of the primary coolant recirculation pumps. Extensive testing of the emergency core cooling systems and natural circulation capability confirmed those design features. All other aspects of the plant were based on the ABWR design. GE submitted the SBWR design to NRC for initial review but did not pursue a final design approval or design certification.

GE re-directed the program to develop a higher unit power version, called the ESBWR[18], rated at 1380 MWe. The effort is being carried out under the auspices of a European

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[16] "Overnight " costs exclude inflation and the interest costs of borrowing money.
[17] Duncan, J et, al., "ASBWR, An Advanced Simplified Boiling Water Reactor", Proceedings of International Topical Meeting on Safety of Next Generation Power Reactors, Washington, May 1988

[18] ESBWR, Using Passive Features for Improved Performance and Economics", European Nuclear Conference, Nice, France, October 1998.

industrial group. In addition to the cost benefits of economy of scale, further R&D identified means of increasing the natural circulation capability significantly. The capital cost of the ESBWR is greatly reduced from the SBWR. Detailed cost estimates have not yet been developed, but GE estimates that the cost of the nuclear island[19] will be half that of the SBWR.

(e) Pebble Bed Modular Reactor (PBMR)

The PBMR in its current form is under development in South Africa by Eskom, the national power company, in collaboration with BNFL and Exelon. The Eskom design builds on a history of pebble-bed technical development in Germany, the US, and China, as well as a longer base of gas-cooled-reactor experience in the US, the UK, and elsewhere around the world.

The concept is an individual unit with small power (110 MWe, 265 Mwt), but intended to be deployed in groups of ten at one site that taken together would generate 1100 MWe and that would share many safety and operating facilities, including a common control room. The fuel consists of graphite pebbles about the size of a tennis ball (60 mm diameter), inside of each of which are about 10,000 individual ceramic-coated fuel microspheres about 0.9 mm in diameter. The ceramic coating will not melt at the highest temperature able to be reached by the fuel, so that each individual tiny fuel sphere is designed to contain the radioactivity within it under all accident conditions, thereby obviating the need for any other barriers (such as a containment) to keep radioactivity from the environment in upset conditions. The fuel itself is low-enriched uranium-dioxide within the specially designed graphite layered spherical package, and the graphite in the fuel pellets serves as the moderator for the chain reaction. The fuel particles are designed and plan to be manufactured with a goal of achieving integrity to contain their entire radioactivity throughout their lifetimes.

The tennis-ball-sized pebbles are contained in a reactor vessel through which they continuously circulate downward by gravity, being put into the top of the "bed" and removed from the bottom, much like the sand grains in an hourglass. At any one time, about 400,000 pebbles are present in the system. Each pebble is analyzed for burnup as it is removed at the vessel's bottom, and is then recirculated back to the top, making about 10 passes lasting a few weeks each down through the reactor vessel before the uranium burnup is sufficient that it is removed from service as spent fuel. The coolant is circulating helium gas, which picks up heat as it is forced through the pebble bed, and then goes to a direct-Brayton-cycle gas turbine to generate electricity. The design concept has room to store 40 years' production of spent-fuel pebbles in vaults beneath the reactor in dry storage.

A crucial feature of the Eskom design is that although active control rods are used, reactivity control can be achieved passively in the event of a loss of coolant flow, which

[19] For a GE-designed reactor, the nuclear island consists of all systems and components inside the reactor building, including the reactor, safety systems, boiler, and containment.

is the major upset[20] scenario of concern. Under loss of coolant flow, the negative thermal reactivity coefficient of the pebbles would passively force the shutdown of the chain reaction. The final temperature that the pebbles would reach in such a loss-of-flow transient would be very much below the temperature at which the tiny fuel spheres would lose their integrity.

Another crucial feature of the design, which relies on the small size (small thermal power), is that although active heat-removal systems are provided, they are not necessary to keep the core cool in upset/accident conditions: the reactor core is designed to cool itself passively by conduction and radiation through the structure to the environment.

The Eskom design team thus claims that very little in the way of "safety grade" equipment is necessary, given that the reactor can both scram itself and cool itself under all design-basis-accident conditions. This, along with the absence of an expensive containment structure and the economies of deploying ten PBMR units of 110 MWe each into one 1100-MWe station, lead to a design that is intended to compete on electricity generation cost with natural gas worldwide.

The Eskom team has completed their design and is now in the process of seeking regulatory approval from the South African regulatory agency. If their aggressive schedule can be kept, they expect to complete one demonstration PBMR module in South Africa in about 3 to 4 years. The Germans have demonstrated that the fuel microspheres can be manufactured in a quality standard that significantly exceeds that necessary for the Eskom safety case. Whether this experience can be replicated at a very large scale and sustained in the manufacturing process involving production of the billions of fuel microspheres required for each core loading remains to be demonstrated.

(f) HTGR

The high temperature gas reactor (HTGR) is not a new basic design, since such reactors have been built decades ago in the United States, with Peach Bottom shut down in 1974 and Fort St. Vrain in 1989. However, newer designs have been advocated for disposition of the plutonium from dismantled nuclear weapons. The newer designs use a direct Brayton cycle, avoiding the need for steam generators, while continuing to use helium and ceramic-coated fuel pellets imbedded in fixed graphite columns. The plant design has also been modularized and is now called GT-MHR (Gas Turbine Modular Helium Reactor), with a modular unit power output of 285 MWe, four of which make up the full plant rated at 1140 MWe. The only active effort is that in Russia, in association with General Atomics and some funding from France and Japan. The proponents of the GT-

[20] If an event is stopped before it proceeds to reactor damage, for example, if a loss-of-coolant-flow upset does not lead to anything but a benign and safe shutdown state, then it would not be an "accident", but an expected "upset scenario" that is contemplated in the design and designed against. If the system cannot handle the event, then it can lead to an accident.

MHR make the same claims of safety, performance, and economy as do the proponents of the PBMR.

V. Assessment of improvements

(a) Advanced LWR Designs

The advanced LWR designs have substantial improvements in safety, reliability, operability and performance over the present U.S. fleet of LWR nuclear power plants. The summary design descriptions above identify some of the key specific improvements achieved. There are four broad areas of advancement:

• New safety features have reduced the probability of a core damaging accident by a factor of ten or more, have increased the robustness of containment systems in the event of a severe accident, and have eliminated the need for rapid recovery actions by the operator to assure public safety.

• The designs have been simplified, leading to capital cost reduction and improved operability.

• There is greater assurance of steady, predictable operation with high plant availability through improved materials, coolant chemistry controls, on-service diagnostics and inspection techniques, and application of digital technology and human factors evaluations to provide superior instrumentation and control systems and control rooms.

• The design process itself has been enhanced by the application of probabilistic risk assessment methods from the onset of the design effort, providing an integrated and risk-informed approach to the entire design.

The cost of electricity from these plants has also been improved and is estimated to be lower than today's nuclear plants by about 20%. Yet, the capital cost is still too high to be competitive with gas-fired plants in the U.S. rate de-regulated market, assuming present gas prices and no environmental credits, requiring continued efforts to bring down the capital costs.

(b) PBMR

The Eskom PBMR concept has several attractive features, but until a demonstration module is constructed and operated, and also until further evaluation of the safety case has occurred, the concept will not have advanced beyond the design-in-advanced-development stage. Significant experience both with the hardware and with analytical methods for safety evaluation exists from the German experience, and Eskom and its team are actively working to improve the safety case through considerable analysis and some tests. The Germans have also demonstrated that the fuel pellets can be manufactured to a quality standard that significantly exceeds that necessary for the

Eskom safety case -- but whether this experience can be replicated at a very large scale also remains to be demonstrated.

If the concept can conclusively demonstrate the very attractive features of shutting itself down and cooling itself under all design-basis-accident conditions, it should find the public-acceptability issue much easier than for larger conventional LWR reactor concepts. The continuous-refueling feature and the significantly reduced reliance on active equipment for either operation or safety should also make for a high-availability operating cycle.

VI. The Generation IV Initiative

In June 1999, the Department of Energy (DOE) proposed the need for a next generation of nuclear power, which has developed into an initiative known as Generation IV.[21] The goal of the Generation IV initiative is to identify and develop one or more next-generation nuclear energy systems that can be commercially deployed no later than 2030 and that offer significant advances in the areas of sustainability, safety and reliability, and economics.

Generation IV nuclear energy systems research & development (R&D) will be guided by a technology roadmap that will identify R&D required to advance the most promising systems. Nearly half of the technical experts participating in the development of the roadmap are from outside the U.S., and international partnerships will be a vital component of developing advanced nuclear energy system technologies. In addition to the long-term worldwide view of the roadmap, the regulatory, technical, and institutional issues that need to be addressed to support the near-term deployment of new nuclear reactors in the U.S. are also being identified. Recognizing the potential need for additional nuclear electric generation capacity in the U.S. before 2030, the Generation IV program established a separate effort to evaluate nuclear power plant designs that have reached a relatively high state of development and might be deployed as commercial operating units by 2010. Light water and gas-cooled systems are being considered. A Roadmap for deployment of the most promising designs is being developed for inclusion in the overall Generation IV Roadmap.

Technology Goals for the Generation IV Initiative

The development of a set of technology goals that may enable the successful realization of new nuclear energy systems has been an important activity of the Generation IV Initiative.

[21] W. Magwood IV, "Looking Toward Generation Four: Considerations For A New Nuclear R&D Agenda," ANS Summer Meeting Plenary Address, June 7 (1999); W. Magwood IV, "Roadmap to the Next Generation of Nuclear Power Systems: A Vision for a Powerful Future," *Nuclear News*, Nov (2000); US DOE, "Generation IV," website on the Internet at ?http://gen-iv.ne.doe.gov?.

Goals for Generation IV nuclear energy systems are proposed in three areas: sustainability, safety and reliability, and economics. Sustainability goals focus on fuel utilization, waste management, and proliferation resistance. Safety and reliability goals focus on safe and reliable operation, investment protection, and essentially eliminating the need for emergency response. Economics goals focus on competitive life cycle and energy production costs and financial risk.

Sustainability**.** Sustainability is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely into the future. Generation IV nuclear energy systems, including fuel cycles, will be designed to provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production. Generation IV nuclear energy systems also will have as a goal to minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment. Generation IV nuclear energy systems including fuel cycles will seek to increase the assurance that they are a very unattractive and least desirable route for diversion or theft of weapons-usable materials.

Safety and reliability**.** Safety and reliability are essential priorities in the development and operation of nuclear energy systems. Generation IV nuclear energy systems operations will seek to excel in safety and reliability. Generation IV nuclear energy systems will be designed to have a very low likelihood and degree of reactor core damage. Generation IV nuclear energy systems will be designed to eliminate the need for offsite emergency response.

Economics. Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems. Generation IV nuclear energy systems will be designed to have a clear life cycle cost advantage over other energy sources. The goal is for Generation IV nuclear energy systems to have a level of financial risk comparable to other energy projects.

Conclusion

The Generation IV technology roadmap will identify R&D pathways for the most promising concepts for next generation of nuclear energy systems. The roadmap has evolved into an international effort, with the ultimate objective of achieving consensus on the planning and execution of large-scale international R&D efforts for Generation IV. The goals are ambitious, but do indicate the requirements seen by a multi-national group of experts as to what will be required to make nuclear power a preferred approach by 2030.

Section VII: Addressing Concerns about Nuclear Power

Four concerns have been raised concerning nuclear power: economics, safety, nuclear waste, and security.

Economics and Safety

The cost of nuclear-power plants has been perhaps the dominant reason nuclear power stopped growing in the United States. As to what were the main factors driving up the costs, many studies and lengthy debates have not reached consensus. Although requirements imposed after the TMI accident initially were postulated by industry to be a major cost burden, events afterwards led industry to conclude that the improved plant operations actually reduced overall costs. However, US plants took increasingly long to build and final costs rose to unacceptable levels. The new designs discussed earlier are estimated, in several cases, to be much less costly to build, thereby addressing the economics concern. The safety of operating reactors has been excellent since the TMI and Chernobyl accidents. Nevertheless, the new designs include many features to improve the safety of these reactors.

Nuclear Waste

Waste remains a troubling problem. There are two major types of waste associated with nuclear power reactors: in United States terminology, high-level waste (HLW) and low-level waste (LLW). HLW from nuclear power plants is spent nuclear fuel, hot in both temperature and radiation. That fuel is stored in spent fuel pools at the reactor sites after removal from the reactors. In most cases in the U.S., the pools are large enough to contain all spent fuel from the original planned operating life. As pools become full, spent fuel is moved to surface storage at the reactor sites in dry casks. These casks are 18-foot high 11-feet in diameter containers with 29-inch thick reinforced concrete walls and two inch-thick carbon steel liners.[22]

Under federal law, the Department of Energy is required to take title to the spent fuel. Since 1987, all electricity from nuclear power plants has had a surcharge of 0.1 cent/kwhr. This money was to be spent to build a geologic repository, although about one-half has been used for national debt reduction. The DOE plan is to move the spent fuel to a geologic repository being developed at Yucca Mountain, Nevada. Continued controversy concerning both objections from the state of Nevada and technical issues that arose during site characterization has significantly slowed the development of the repository. Originally planned to be opened by the end of the past century, it currently is not scheduled to be opened until 2010 and only the most optimistic proponents believe that date will be met. In August, DOE issued the site suitability report, which is the next step in a process that leads to a Presidential decision to recommend to the Congress that the Yucca Mountain site be used or that the process of site selection begin again.

In the US, reactors are licensed for 40 years. Until a few years ago, utilities planned on shutting down the reactors at the end of this period, and a few reactors were shut down before the end of the license period. However, along with deregulation and higher energy

[22] There are several versions. These are typical dimensions.

prices, nuclear plants are being relicensed for an additional 20 years, increasing the need for more dry casks and the pressure for the federal government to take title to the spent fuel.

Spent fuel in surface dry storage has been determined by the Nuclear Regulatory Commission to be safe for it least 50 years. So long as institutional control is maintained, studies[23] estimate safety can be maintained for several hundreds of years. Nevertheless, not being able to transfer the fuel to the federal government has begun to be a problem in several states. It should be noted that no country has developed a geologic repository for high-level waste. Currently, Finland seems closest to developing one.

Low-level waste can be disposed of in shallow surface facilities since most of the hazard will decay away in less than a century. However, siting such burial grounds has not been possible in the United States in the last 20 years. Currently there are three LLW sites operating: a site in Richland, Washington restricted to use by several Northwestern states; a site in Barnwell, South Carolina open to all states other than North Carolina; and a site in Utah open to all states but only for the lowest level of contamination of low-level waste. Low-level waste sites are used by industries for disposal of radioactive sources used for non-destructive evaluation, by hospitals and other clinical research organizations for disposal of radioactive materials used in both diagnostic and therapeutic procedures, and by nuclear-power plants. By far the largest amount of low-level waste is generated by nuclear-power plants. However, since it became apparent that new low-level waste sites would be extremely difficult to locate, the amount of low-level waste from nuclear-power plants has decreased significantly. This was accomplished by more careful segregation of waste, so that only radioactive contaminated waste has to be taken care of as low-level waste, and by compacting the remaining LLW, which significantly reduces the volume of low-level waste.

Security

Nuclear power poses two concerns regarding security issues: terrorist threats and proliferation threats. Because the nuclear-power plant does contain radioactive materials within the reactor core and the spent fuel storage areas, such plants must be protected against terrorist attacks. There is a constant review by the Nuclear Regulatory Commission of what are the real threats against which plants must be protected as well as training of guard forces to meet those threats. The terrorist attacks of 11 September have heightened the levels of security around operating nuclear plants. Reviews are underway at the NRC and in the Congress to consider what additional security requirements should be imposed. The results may lead to noticeable increases in operating costs and potentially to equally significant costs for new plants.

All isotopes of plutonium can be used to make a nuclear weapon, although Pu^{239} would be the material of choice of knowledgeable weapons designers. Nevertheless, because of the presence of plutonium in all spent fuel, there is a concern that such fuel might be used

[23] "Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges", National Academy Press, Washington, DC, 2001, pp. 25, 115-116.

with the endpoint being a nuclear weapon. This concern is greater if the spent fuel is reprocessed as a means of addressing the spent fuel issue. Reprocessing is done to separate out the fission products, which represent most of the radioactivity in the spent fuel, and have shorter half-lives than the long-lived actinides. This approach is used in Europe, but the US has not reprocessed fuel for about thirty years. In addition to it not being economical (fresh low-enriched uranium is much cheaper), reprocessing separates out plutonium, which is a serious proliferation concern.

VIII. Research Needs

Nuclear reactor research needs have been addressed in two broad reports, one in 1997 by the President's Committee of Advisors on Science and Technology (PCAST)[24] and one in 2000 by the DOE Nuclear Energy Research Advisory Committee (NERAC)[25]. In addition to basic research on materials, instrumentation and controls, and fuel design, both reports call for research to address proliferation, waste, and economics.

IX Further Reading

A selected set of readings, including some from proponents and opponents:

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