Nuclear Energy Research Advisory Committee
(NERAC)
Subcommittee on
Long-Term Planning for Nuclear Energy Research

Long-Term Nuclear Technology Research and Development Plan

SUMMARY

June 2000

SUMMARY

This document constitutes the first edition of a long-term research and development (R&D) plan for nuclear technology in the United States.

Introduction

In 1998, DOE established the Nuclear Energy Research Advisory Committee (NERAC) to provide advice to the Secretary and to the Director, Office of Nuclear Energy, Science, and Technology (NE), on the broad range of non-defense DOE nuclear technology programs. The NERAC recommended development of a long-range R&D program. This R&D plan is a result of that recommendation and is the first of what is expected to be an iterated series of long-range plans for nuclear energy in the Department of Energy.

To develop this plan, 145 nuclear and non-nuclear scientists, engineers, and academics were canvassed for recommendations of R&D topics that should be evaluated and addressed in a DOE nuclear technology long term R&D plan. .A website was established and notices put in technical journals and given at meetings of the community. As a result, many suggestions were gathered to serve as a starting point. Two workshops were held, involving 123 participants from across the involved scientific and technical community to consider and expand on the submitted ideas. These workshops produced summaries of specific areas, which are included as appendices to the report. A writing committee composed of representatives of the workshops drafted a report. This draft report was circulated twice to the writing group, after which the third draft was sent to all workshop participants for their comments. This report is a result of that process.

The focus here is not on next year's budget but on what is necessary to develop over the next 10-20 years. Although this plan is intended to comprehensively focus on DOE's non-defense nuclear technology, it simultaneously (a) excludes some aspects of DOE's non-defense nuclear technology program that do not involve R&D, e.g., landlord at sites, or nuclear technology activities that are being addressed by other reports, e.g., accelerator transmutation of waste (ATW), and (b) includes some closely related nuclear technology activities that have defense or national security implications.

Within DOE's overall nuclear technology mission, DOE-NE has a mission to create and advance nuclear technology and infrastructure for non-defense and related closely related defense applications. The DOE-NE mission leads to the following areas of responsibility:

- Enhance nuclear power's viability as part of the US energy portfolio. The issues for this R&D plan are what elements of nuclear energy should be supported and at what level.
- Sponsoring needed R&D and coordinating this work with other agencies.
- Providing the technical framework to implement US nuclear policies in support of national and global security.

- Supporting selected other missions, such as assuring a supply of medical isotopes and of space power systems
- Maintaining necessary national laboratory and university nuclear infrastructure, including user facilities, such as test research reactors, test loops, and other research instruments or machines.
- Supporting the education system in nuclear engineering and science.
- Maintaining sufficient US expertise to assure an effective role in the international community and to support the needs for nuclear expertise to meet DOE defense and environmental missions.

In many respects, DOE-NE's role is to support and to catalyze research which, if successful, will be scaled up or applied by others. DOE-NE's focus should be on planning and sponsoring research in partnership with industry, thereby helping to broker with other sponsors to pursue promising results. When a concept is ready for the prototype or demonstration facility stage, DOE-NE should help transition the concept to whomever will implement or commercialize the results. A Government-industry partnership, leveraged with substantial international participation, would be appropriate to undertake R&D, especially where market competition is critical to success or major development and demonstration of advanced nuclear technologies is required.

NE provides user facilities, such as research reactors, test loops with provisions for inserting samples under known (controlled and measurable) parameters, and other research instruments or machines that are not commonly available but may be needed by the civilian and national security research community. NE has a role in insuring isotopes are available as needed by the community. NE is responsible for insuring that power and heat sources are provided to support NASA’s deep space and planetary explorations.

Lead responsibility resides outside of NE for defense applications, safeguards and nonproliferation activities, environmental management and waste cleanup, and Navy nuclear propulsion systems development.[1] The department has a lead role in insuring that excess nuclear weapons material is safeguarded and, in a joint program with Russia, that such material is made much less accessible. And, of course, the DOE provides stewardship for the nation's nuclear weapons stockpile and for the development of nuclear power systems for the US Navy. This R&D plan does not address these national defense areas or the program for the final disposition of spent fuel at a geologic repository, the lead responsibility for which is carried by DOE organizations other than NE.

---

[1] However, nuclear R&D conducted in the other DOE offices provides opportunities for collaboration in such areas as cleaning up the wastes from the decades of nuclear weapons related activities at DOE sites and for providing technical support of U.S. bi-partisan global nuclear policies to assure acceptable international practices in nuclear power plant safety, radioactive waste management, and proliferation resistance.

The report uses terms for categories of nuclear plants, defined as follows:

Generation I: Prototype and demonstration plants built through the 1970's.
Generation II: The existing fleet of LWR and HWR plants, except for the few Generation III plants already in operation.
Generation III: Advanced LWR plants, both evolutionary and passive.
Generation IV: Revolutionary advanced nuclear plant designs with a variety of fuels, coolants, moderators, and configurations.

Goals

Although nuclear energy has been applied for over 40 years, many technical issues remain. Research on these issues is needed for continued safety and improved economics and a deeper understanding of how new knowledge can contribute to the many future applications of nuclear energy. The following summarizes the goals of the R&D programs recommended in this report.

Basic research: develop new technologies for nuclear energy applications; educate young scientists and engineers; train a technical workforce; and contribute to the broader science and technology enterprise.

Advanced fuel cycle R&D: develop (1) improved performance and advanced fuel design for existing light-water reactors (Generation II and Generation III) and (2) advanced fuel designs and related fuel cycle requirements for advanced Generation IV reactor designs.

Plant operations and control: develop instrumentation, controls, information management and decision making systems for use in nuclear power plants that employ or adapt the latest technological advances in digital instrumentation and controls, communications and man-machine interface technology including micro-analytical devices and/or "smart" sensors, on-line signal validation, and condition monitoring.

Nuclear power R&D: develop advanced nuclear reactor technologies that will allow the deployment of highly safe and economical new nuclear power plants that would be a competitive electricity production alternative in the U.S. and foreign markets, while being responsive to environmental, waste management, and proliferation concerns.

Isotopes and radiation sources: improve the quality of life and economic competitiveness of the U.S. for research, medicine and industry in the (1) production and inventory of isotopes, (2) research and development on isotopes, and (3) fostering the application of isotopes. and (4) management of national resource isotopes.

Space nuclear power systems R&D: support DOE's role as the only agency where space nuclear power systems are developed as it continues to supply radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs) for NASA identified missions and to establish a DOE policy to support space nuclear power and propulsion systems.

Major policy issues which arise in this plan:

(1) What is the role of the federal government in funding research where there is an existing industry? This pertains both to nuclear power and to isotopes. Consistent with U.S. government policy in other areas, such as fossil energy R&D, we assume there is a definite responsibility to assure that research be funded that is important for the US and where it is unlikely that industry will fund it.

(2) What is the role of DOE in ensuring that nuclear power remains a major element in the US energy portfolio? We assume that is a DOE responsibility.

(3) What is the responsibility of DOE to ensure that a supply of qualified personnel be available to handle the many tasks associated with the application of nuclear energy? We assume that is a DOE responsibility.

(4) What is the responsibility of DOE to ensure that necessary facilities be maintained at universities and national laboratories to both perform research and to educate students? While another NERAC group is examining what those needs would be, we do assume this is a DOE responsibility.

(5) Finally, what should be the future role of nuclear power in space exploration? We make no assumption on this issue.

Programs covered in the report

Basic Research

Today's U.S. reactors, which are based largely on 1970's technologies, operate under close supervision in a conservative regulatory environment. Although the knowledge base is adequate for these purposes, improvements in our knowledge and reduction of the inherent uncertainties could bring cost savings in current reactor operations and reduced costs for future reactors. Furthermore, they could enable innovative designs that reduce the need for excessively conservative and costly factors of safety, and lead to improved efficiencies, superior performance, enhanced safety and reliability, and significant extensions in safe operating lifetimes. Future reactor technologies are likely to involve higher operating temperatures, advanced fuels, higher fuel burnup, longer plant lifetimes, better materials for claddings and containment vessels, and alternative coolants. To implement such features, substantial research in fundamental science and engineering must be carried out to supplement applied research specific to individual promising design concepts. Such fundamental research need not and should not be directed to any specific design. Although motivated in part by the need for new nuclear reactor system designs, the research would also have far-reaching impact elsewhere in engineering and technology.

Five broad topics are identified for extending current basic research into new frontiers:

1. the environmental effects on materials, in particular the effects of the radiation, chemical, thermal environments, and aging;
2. thermal fluids, including multiphase fluid dynamics and fluid-structure interactions;
3. the mechanical behavior of materials, including fracture mechanics, creep, and fatigue;
4. advanced materials, processes, and diagnostics; and
5. reactor physics.

Nuclear Power

From a global perspective, it is clear that substantial increases in the demand for total energy, and electricity in particular, will occur over the next several decades, especially in the developing countries. In the United States nuclear power is a major source of electricity generation and will remain so for the foreseeable future. Nuclear power is a source of reliable non-emitting energy that has the potential for expansion on the scale required to address clean air and climate change concerns**.** The use of nuclear power also has significant global security implications that the U.S. government has addressed by policies fostering international protocols and standards for nuclear safety, radioactive waste management, and non-proliferation. All these require U.S. technical leadership.

Whether the world can successfully control both type and level of greenhouse gas emissions and any consequent global climate effects will depend primarily on the rate of increased use of non-emitting technologies and on energy demand growth in the developing world, particularly on those countries with major coal resources. Nuclear power-has been an important contributor in reducing greenhouse gas emissions in the United States, in Asia, and in Europe, especially in France. How much of a contribution nuclear power can make in the future depends on the economic competitiveness of new plants.

NE has important strategic roles in the following four areas related to development of advanced**,** and improvement of existing**,** nuclear power systems:

1. research on advanced reactor concepts with focus on concepts that show promise over existing designs in improved economics, safety, non-proliferation attributes, and waste characteristics;
2. development of virtual construction capability, advanced information management, and risk-based safety methodology to achieve economic competitiveness in the U.S. market for Generation III reactor systems;
3. development of processes and technologies, including new fuels, that can be utilized to improve the operating efficiency of existing domestic reactors; and
4. development of systems with increasing proliferation resistant fuels that can be utilized in existing foreign research reactors.

R&D on Generation IV reactors will require, after a period of evaluation and screening of innovative concepts fostered in the NERI program, a substantial amount of experimentation, including extensive irradiation testing of advanced fuels. DOE should focus on research, development, and demonstration for domestic reactors that would improve the efficiency, reliability, and cost of those plants through new operating related processes, technological advances, and fuel design improvements, including higher burn-up fuels, that can be used in advanced LWRs (Generation III) and existing PWRs and BWRs **(**Generation II). Research and development of improved and higher burnup fuels for existing reactors must be accompanied by parallel efforts to ensure that these improved fuels can be licensed and utilized in a timely manner in reactors under existing and extended licenses.

The section on nuclear power reactors has three subsections: advanced fuels, instrumentation and control, and reactor design and economics.

Advanced Fuel Cycles

The scope of research and development selected for the area of advanced fuels encompasses the following three fuel cycles: 1) uranium-based once through; 2) uranium based closed cycle (with emphasis on dry processing); and 3) thorium based fuel cycle. In each of these fuel cycles, R&D on surplus weapons materials (HEU and Pu) disposition should be considered.

The two primary areas of proposed advanced fuel R&D are 1) improved performance and advanced fuel design for existing light-water reactors (Generation II and Generation III), and 2) advanced fuel designs and related fuel cycle requirements for Generation IV reactor designs. The scope of R&D includes a variety of thermal and fast spectrum power reactor fuel forms, including ceramic, metal, hybrid (e.g., cermet, cercer), and liquid, as well as fuel types, including oxides, nitrides, carbides and metallics. Enabling technologies such as advanced cladding, water chemistry, and alternative moderators and coolants also should be considered. The fuel cycle research includes consideration of advanced enrichment technologies for fuel and burnable absorbers and considers the impact of fuel cycle options on the proliferation of nuclear weapon materials, waste generation, waste form, waste storage and disposal. The R&D scope also includes development of higher density LEU (< 20% U-235) fuels for research and development reactors.

In the near-term (5-10 years), a primary focus of the R&D is on achieving higher burnup fuel for existing and advanced light water reactor technology (Generation II and Generation III reactors) and higher density fuels for research and test reactors. Many areas of research should be pursued immediately regarding fuel form and fuel type performance for potential Generation IV reactor concepts. Within five years, it is assumed the fuel cycle R&D would be fully integrated with any specific Generation III and IV reactor designs either emerging from the screening of NERI R&D innovative concepts or under further development by DOE.

Plant Operations and Control, including Probabilistic Risk Assessment, Human Factors, & Organizational Performance

Topics covered include research to develop, adapt, and/or validate

- advanced instrumentation, sensors, and read-out capability**;**
- fully integrated controls, with advanced and effective human-machine interfaces;
- integrated, phenomenological, real-time, and/or virtual-reality computational models and simulation tools; and
- probabilistic risk assessment
- organizational performance research
- human-factors research.

Advances in information technology, sensors, instrumentation, controls, communications, simulation, and numerical models provide considerable potential for improving the safety, reliability, and economics of nuclear power plants. Advantage should be taken of the many billions of dollars per year invested by industry and government in advancing computational and I&C technologies that are producing ever-more capable, inexpensive, fast, and reliable computers, sensors, materials, simulation models that can be applied to nuclear power. Benefits are expected from design through construction, operation and decommissioning. Gains would accrue to the current fleet of plants as well as to Generation III and IV plants. Detailed, timely, and accurate measurements of plant performance can improve safety and economics by allowing operations and maintenance to be fact-based and by eliminating unneeded margins. Thoroughly validated simulation codes and sophisticated databases would make it possible for the experience and wisdom learned across the industry and throughout a plant's life to be used in real time to support design, operations, maintenance, and decommissioning decisions. A systematic and sophisticated understanding of the role and behavior of plant personnel in normal and emergency situations could help guide nuclear power plant operations, including operator training. Improved control rooms would provide a more intuitive and natural human-machine interface with the potential for better and safer operations with fewer operators and maintenance personnel. In addition, research progress can have large beneficial effects on new plant construction by reducing commodities (e.g., cables) and installation effort.

Reactor Technology and Economics

The goal of this research and development program is to develop advanced nuclear reactor technologies that will allow the deployment of highly safe and economical new nuclear power plants. These would be a competitive electricity production alternative in the U.S. and foreign markets, while being responsive to environmental, waste management, and proliferation concerns.

The overall objective of this research and development program is to provide the technical basis for competitive Generation III and Generation IV nuclear energy in deregulated electricity Generation markets. For Generations III and IV, the specific objective is 3 cents/kWh busbar cost, down from the present 4.1 cents/kWh. Generation

III and Generation IV reactors are envisioned as products for the 21st century world market. As such, the development and testing of Generation IV technology would benefit greatly from international participation. The recommended funding profile assumes considerable international leveraged-funding, at least equal to the U.S. effort.

The plan's R&D basis is that there are R&D results generic to both Generation III and IV that should be available before 2010. Further, there are other results, specific to preparation for the demonstration of Generation IV systems, that will not reach fruition until after 2015. The overall results, therefore, will contribute to the economic competitiveness of Generation III systems deployed in the near term and the introduction of Generation IV systems in the longer term. Therefore, a research strategy is recommended having both near-term results (for deployment in the next 5-15 years) and long-term results (for deployment in the next 15 years and longer).

The recommended R&D program includes advances in system design and methodologies and technologies associated with the design, fabrication, manufacturing and construction, and operations and maintenance of nuclear plants to reduce costs, while conforming to safety, environmental, and non-proliferation requirements. Research topics are organized in four categories:

- System Design and New Concepts,
- Capital Costs and Construction Time,
- Efficiency/Output, and
- Generating Costs (including Capacity Factor and Operation and Maintenance Costs).

The reactor technology research program is organized into major phases: (1) starting with a focused review of technologies to reduce the capital costs of Generation III plants, and an exploration of a variety of Generation IV reactor concepts; (2) conduct of key technology research, progressing to a selection of one or more leading concepts; and (3) a culminating major focused construction program requiring testing and prototype construction and operation for Generation IV to demonstrate market readiness.

The initial phase of the program (2002-6) grows out of NERI and prior design activities and explores a broad portfolio of system design candidates for longer-term, revolutionary Generation IV plants, and options for major capital cost reduction for deployment of Generation III plants. The system design effort will serve to identify key technology issues for focused research. In addition, the research program will address key technology issues for Generation III and IV plants that respond to capital and generation cost issues, including advanced fabrication and construction technologies and modularization approaches.

Assuming continued US government support, the second phase of the program (2007-10) would continue the focused research program, which, if successful at responding to the key technology challenges, allows for a down selection to one or more promising system Generation IV concepts for further development, and provides final plans, but not government funding, for construction of one or more Generation III plants in the United

States. In addition, the technical basis for the licensing methodology for advanced Generation IV systems will be developed.

In phase three, beyond 2010 and applicable to Generation IV, major components and systems will be designed, tested and demonstrated, the formal Title design will be completed, and the design will be submitted for licensing approval.

A final phase will be needed as phase three is completed, beyond 2010. *Given sufficient private and public funding commitment*, a prototype plant would be ready to be constructed to prepare the Generation IV plant design for broad market application.

Isotopes and Radiation Sources

Radioactive and enriched stable isotopes, including radiation sources such as neutrons from reactors or x-ray generators, are essential for several critical areas of national importance to health, safety, national security, and industrial development and international competitiveness. These include the following:

- Medical applications: Diagnosis and therapy of a range of diseases relies upon
- isotopes, both applied directly for treatment and for diagnosis.

- Industrial usage: There are numerous vital applications of isotopes, including
- industrial radiography, measurements of chemical, elemental, or physical parameters
- of samples and bulk materials, thickness gauging, runway safety lights, smoke
- detectors, initiating chemical reactions, and sterilization.

- Research: Research relating to medical, industrial, agriculture, and the natural and
- physical sciences use isotopes as tracers or as external radiation sources. Examples
- include biomedical research, materials testing, the environmental transportation of
- isotopes, and others.

- Federal programs: Isotopes are needed to support the work of government agencies,
- primarily related to national security applications.

Radioactive and enriched stable isotopes and radiation sources are widely and increasingly used in medicine, research and industry. DOE-NE has a major role in isotope research and production. Overall, the isotopes managed by DOE, which as addressed in this document include radiation sources, fall into three categories:

- *Programmatic*: Isotopes that have identified uses by specific programs.

- *National Resource*: Quantities of stable and radioactive isotopes that are used by multiple programs or that are presently surplus but difficult to recreate.

- *Waste*: Materials that have no present programmatic use and where the potential for

- any future use is so low that it is not cost-effective to separate and maintain them as a national resource.

In the future, DOE-NE's isotope mission should be broadened to be the following:

> Improving the quality of life and economic competitiveness of the U.S. through isotopes and radiation sources for research, medicine and industry. DOE-NE's roles will include (1) production and inventory of isotopes for research, medicine and industry, (2) research and development on isotopes, (3) fostering the application of isotopes, and (4) management of national resource isotopes.

DOE should aspire to the long-term vision of being the leader, but not controller, of an enduring, cost-effective isotope program with visible public benefits.

The following strategies are recommended to support isotope research:

1) Focus on isotope applications not being supported by other Federal programs

2) Invest in R&D to improve isotope production, processing, and utilization.

3) Be responsible for managing U.S. national resource materials.

4) Lead a multiprogram effort to assess responsibilities for the current isotope and radiation source infrastructure with the goal of streamlining responsibilities.

5) Invest and organize to meet the needs of isotope researchers.

6) Maintain the current infrastructure while planning for new capability within the next two decades.

Space Power Systems

NE has an important role in providing the radioisotope power systems, including the Pu-238 used to fuel such systems, conventional and advanced hardware used to convert decay energy to electricity, and, in the future, may provide reactor-based space power systems for situations requiring larger amounts of power.

As NASA begins to plan more ambitious missions, it is important to assess the potential application of a broader range of nuclear energy sources for civilian space missions. These include further developments of:

- Advanced radioisotope power systems to increase the operational efficiency of the units to reduce the demand for the radioisotope used to fuel these systems;
- Space nuclear power reactors to provide long-term operational electricity to enable missions requiring significantly more power than possible from conventional means

(including chemical, batteries and solar) or where conventional means are impractical; and
- Nuclear reactors for direct propulsion applications.

DOE retains the unique position within the U.S. Government of being the only agency where space nuclear power systems are developed. A broad set of research needs are essential to make space nuclear power and propulsion systems possible. First, there is a need to continue development of radioisotope systems to ensure their availability for future applications. Radioisotope power systems and heater units will continue to have important functions in space and reliable Pu-238 supplies will be essential. Second, there is an important need to establish a continuous technology research and development program focused on providing the fundamental understanding of the broad base of technologies that may be needed for a wide range of missions for both radioisotope and reactor power systems. Third, specific reactor systems for electrical power production under varying conditions for nuclear electric propulsion and surface power need to be developed. This program should be directed toward developing a flight-qualified fission electric power system in the 5 - 50 kWe range that would be suitable for power production and nuclear electric propulsion (NEP). Fourth, further developments in the technology and systems required for direct thermal propulsion are needed. The goal of this program would be to establish the technology for a nuclear thermal rocket (NTR) fuel element with characteristics of 5-30 MW/l power density and 3000 K outlet temperature.

Education and Training

Perhaps the most important role for DOE-NE in the nuclear energy area at the present time is to insure that the education system and its facility infrastructure are in good health. This research R&D plan identifies important research topics whose funding can improve the potential for and the use of nuclear energy by the United States. But without adequate facilities and a sufficient number of qualified researchers, the research will not be done. Without a continued supply of new graduates in nuclear energy related areas, it will be a major challenge to continue to provide society with the benefits associated with the many applications of nuclear energy.

Nuclear expertise and nuclear engineering programs in United States universities have been substantially curtailed. The remaining expertise and programs are also at risk of being lost in the next decade, or less. Without concerted action by DOE, supported by OMB and the Congress, most of the existing nuclear engineering programs will soon evaporate or be absorbed and diffused in other engineering disciplines. While cross-over from other engineering and science disciplines will be necessary and healthy, in the long term educated nuclear engineers and scientists will be necessary to meet the needs described in this plan. To reverse the decline will require generating enough excitement on campuses to attract excellent students and faculty. NERI has that potential. Direct support to researchers at academic institutions is needed, not only support provided through projects run by industry or the national laboratories, valuable as these last have been and will continue to be.

NERI and NEPO

The President's Committee of Advisors on Science and Technology (PCAST) report on Federal Energy Research and Development for the Challenges of the Twenty First Century (November 1997) recommended that the Department of Energy initiate the Nuclear Energy Research Initiative (NERI) to support new and innovative scientific and engineering research. The report also recommended that "DOE work with its laboratories and the utility industry to develop the specifics of an R&D program to address the problems that may prevent continued operation of current plants".

NERI is a research program aimed at incubating new ideas while helping to arrest the decline of nuclear energy researchers. Research areas are identified in a request for proposals from academia, national laboratories, and industry, with collaboration encouraged. Awards are based on merit, judged by peer review. While addressing important topics, the NERI can revitalize nuclear energy departments, retain high quality researchers in academia, national laboratories, and industry, and encourage and support the students who will be the base for the future use of nuclear energy in all its applications. This R&D plan builds on the NERI concept, adding more areas and more details for future calls for proposals, as well as identifying some specific, long-term programs which will require stable funding to achieve success and hence are beyond the scope of the NERI program.

NEPO is a jointly funded DOE-industry program aimed to address the problems of current U.S. nuclear plants. The program has been formulated by selection of high priority projects from the "Joint DOE-EPRI Strategic R&D Plan to Optimize U.S. Nuclear Plants". The selection of projects is recommended by a Coordinating Committee of industry and government nuclear power experts and reviewed by NERAC. The results of the program will contribute to the goals established in this Plan for the Generation II and III plants.

Other Key DOE Nuclear Energy Missions

DOE has many other activities in the nuclear energy area, some of which involve NE and others that do not. This first effort at a long range R&D plan does not attempt to include these other areas.

<u>Waste Management</u>: Worldwide, the disposal of radioactive waste is a difficult challenge. Nowhere has this become more evident than in the United States. One of the workshops for this R&D plan discussed four types of radioactive materials: high level waste (HLW), defense wastes, surplus fissile weapons material, and low level waste (LLW).

Some of the associated issues require policy decisions:

- agreement on what is interim storage, enabling DOE, states, and owners of nuclear power plants to develop plans for stored HLW;
- DOE taking title to commercial spent nuclear fuel; and

- DOE becoming an active participant in an international cooperative organization to address what to do with commercial spent fuel.

ATW: The program for accelerator transmutation of waste is now in NE. A recent DOE roadmap report presented a six year research program for $280 million, a substantial program. Interest is not confined to the United States. Sizable programs exist in the European Union and Japan. Although at this size the ATW could become the major NE program, it is not included in this R&D plan both because the planning has been laid out in the roadmap report and, if successful, the program would be for waste management.[2]

Materials Disposition: As part of the programs to reduce the nuclear arsenals of the United States and Russia, substantial amounts of HEU and weapons-grade plutonium are being recovered from dismantled nuclear weapons. The HEU can be blended with depleted uranium to produce low enriched uranium to use in making fuel for nuclear reactors. The plutonium poses more difficult problems but can be fabricated into standard mixed oxide fuel and used to generate electricity in operating light water reactors.

International

All R&D programs can benefit by international participation and coordination, including exchange of information and use of facilities and sharing funding.

Funding

It is not difficult for the research community -- in any discipline -- to generate a lengthy list of projects. Similar to another aphorism, proposed research can expand to fill any budget. However, after substantial thought and discussion, the participants in developing this R&D plan narrowed the desirable projects to those judged to be most important. No efforts were made to retain "nice to do" projects. Also, the plan attempts to be realistic by not exceeding what might be possible, while using as a floor what is necessary if the goals outlined here are to be achieved. The approach used to develop a budget was to estimate what annual funding would be necessary in 2005 for the programs described above. Recognizing this would require a ramp-up from current funding, the amounts are judged to be well within reason for the DOE energy and, to a lesser extent, science business lines. The 2005 funding is assumed to be stable, at least at that level, as well as recognizing that some programs would require a decision (in 2010 or later) as to whether to commit larger funding amounts for full scale development and possible prototype construction.

---

[2] A differing view within NERAC is that the committee should provide a strong statement that in effect says we view ATW R&D as a very low priority for DOE. In this view, any research should be limited largely to paper studies until it can be shown that a) ATW is cost effective, b) the reduction in radionuclide releases from a repository would exceed the releases from routine operation of an ATW fuel cycle, and c) the required spent fuel processing that is associated with an ATW fuel cycle does not increase proliferation risks in the near term.

The **basic research** described is long-term. Very little research that would have direct application to the issues identified here is currently being supported or conducted, although some broader activities potentially have some relevance. The topics can encompass many different program offices within DOE. It is estimated that a sustained program of *new* funding of about $54 M per year is needed. Additional capital funding for facilities is estimated to be about $6 M per year.

The **advanced fuel/fuel cycle R&D** should be considered a 20-year program, because of the time period required to prove new fuel concepts. This program should produce qualified fuel products for existing light water reactors within 10 years or less and Generation IV fuel products within 15 to 20 years. The second track of the R&D program for existing plants would extend over about a 10 to 15 year period. For current budget planning purposes, it is assumed that four fuel type/fuel cycle options for Generation IV reactors and two fuel type options for existing LWRs would be studied over the first five years of the program. It is further assumed for budget purposes that after these first five years, full-scale R&D programs culminating in qualified fuel products would be pursued on two Generation IV fuel type/fuel cycle options and one existing LWR fuel option.

Within the bounds of a program design as outlined above, it is estimated that the budget required over the 20-year period would be about $750 million, including about $100 million for research reactor and other facility modification costs. The facility expenditures relate to having the TREAT facility available for testing higher burnup fuel for existing reactors and for potential Generation IV fuels. For Generation IV reactors, loops in TREAT for testing fuels to be used in potential gas or liquid metal reactor designs would need to be provided. Specifically, two loops of TREAT would be required for a total of $20 million over the first five years. Also, the availability of a thermal spectrum environment, e.g., the advanced test reactor (ATR), is considered necessary for testing purposes. About $10 million would be needed for this use of the ATR. Similarly, if a fast spectrum reactor emerges from the screening phase, then a fast flux environment e.g., the fast flux test facility (FFTF) will be needed.

Over the next five years, expenditures of about $40 million/year will be required, which includes about $12M for higher burnup fuels in existing reactors. As part of the industry-government collaboration on the existing reactors, about $6M in contributions from the private sector (possibly in-kind) would be provided to supplement the $12 M in the above budget.

Plant operations and control, including PRA, human factors, and organizational performance, in the near term, to accomplish the programs described, DOE-NE should invest $18-20 million per year in sensor, instrumentation, controls, simulations, modeling, human-factors, PRA, and organizational performance research, about two-thirds through NERI (or similar merit-based, competitive process) and one-third through NEPO or some other mechanism that selects quality proposals and requires at least 50-50 matching by industry. Some of the cost-shared research should address issues associated with licensing technologies for use in nuclear power plants. By FY 2005, the annual funding level should reach $30 million, and DOE should consider making these technologies the focus for a specific program.

DOE should establish a facility (at one location or multiple linked sites) to support the research, development, and testing of advanced I&C, modeling, simulation, and control-room components and concepts. This facility should include virtual reality modeling and simulation capability. The first step, to specify the features for the facility and to estimate its cost, should be completed in FY2001, and the facility should be available before 2005. The facility should be able to be built within the funding recommended above.
In addition, DOE-NE should take responsibility for ensuring that federal, industrial and international R&D efforts on nuclear power plant-related I&C, modeling, simulation, and human-factors are well coordinated.

Nuclear power technology. The funding profile for the first phase of the R&D plan to achieve economically competitive nuclear power reaches $60 M annually by 2005. The total five year cost for phase I (2002-2006) is $250M. The funding profile for phase II should be in the range of $100M annually (2007-2010). Funding for phase III, which includes major component testing, would require substantially larger funding, the magnitude of which depends on several factors including the availability of appropriate test facilities. This may be in the range of $150M annually.

Isotopes and radiation sources. The following funding is recommended for the objectives described:

- Isotope R&D: Increase DOE-NE research funding to $10M/yr over the next five years to identify new applications of isotopes and radiation sources
- Production and Inventory: Increase the DOE-NE isotope production and inventory budget by $10M/yr to support efforts to produce research isotopes and to refurbish and upgrade the existing isotope production and inventory infrastructure.
- Fund a $2M/yr evaluation of existing isotope-related supply, demand, and infrastructure leading to a design and budget request by 2003 for a new and/or upgraded isotope production and inventory complex. The cost of the complex is about $250M, but this value could change substantially depending on the scope of the complex that will not be known until the evaluation is complete.
- Isotope Leadership: Fund a DOE Isotope Leadership Office having a mission different from the existing DOE-NE isotope production and sales function at $1M/yr and sustain it at this level, adjusted annually for inflation.

All of these amounts are in addition to funding that will be required to assume responsibility for maintaining national resource materials obtained from other organizations. The amount of this new funding cannot be estimated until a decision process and criteria for retention of national resource materials is established and implemented.

Space. It is difficult to estimate the resources necessary to reach the plan's long term objectives without a complete plan for development. However estimates can be made on the approximate totals for steady state funding levels in each of the target areas. It is estimated that the space radioisotope power system research, development and production activities will require between $150M to $200M over a 10-15 year time period. The electrical power reactor research and development program is very roughly estimated to require on the order of $1 B to develop a flight qualified system, and the nuclear propulsion program will need an investment of approximately $1 B over a similar period of time. Utilization of previously developed space nuclear power and propulsion facilities and collaborations with basic nuclear science and engineering activities discussed in other sections of this report for development and testing can temper some of these expenses. Of course, these cost estimates depend strongly on the assumptions for the design and degree of ground testing required. Facility costs will depend on whether new or modified facilities are needed.

It must be noted that no comprehensive system development cost analysis has been done recently for any particular system. Until such studies are conducted the above cost estimates must be considered to include fairly sizable uncertainties. It is recommend that development and facility studies and evaluation should be a primary DOE objective in the area of space nuclear power development.

A continuous technology research and development program funded annually at the $25 M level would provide a fundamental understanding of the broad base of technologies needed for a wide range of missions for both radioisotope and reactor systems.

Total

In developing this plan, several fundamental assumptions were made:

- We estimate that the programs recommended here would be above a nuclear energy R&D base of what is currently about $55 million per year. Funds recommended are new monies, not reprogrammed from other related efforts.

- The research work cannot go forward without facilities, researchers, and students. The research would provide a foundation for funding these other elements, but without these other elements present, the research could not be done.

As is clear from several of the sections, focusing on a single year, 2005, neglects the difficult issues associated with how to ramp up as well as not addressing the longer term commitment. However, taking a one-year cut does enable comparison with current funding to give an initial reality check.

We also include a lower total level, not because we believe there is excess in what is estimated here, but because policy makers may decide this is too ambitious a program. Since the items listed here were deemed to be most important in each area, further reductions should assess priorities across areas, for example, by deciding which missions of DOE should not be supported.

In summary, this plan estimates the following funding in 2005 (in FY2000 $) if the programs are to be accomplished:

Area	$ (in millions)	Comments
Science and Engineering	60	
Advanced Fuels	42	Includes $20 M for TREAT and $10 M for ATR
Plant Operations & control, etc.	30	
Nuclear power	60	
Isotopes	23	Does not include funding for a new facility.
Space Nuclear R&D	25	
Total:	$240 M in 2005	

This total, $240 M, is to be compared with the current programs in these areas, about $55M, indicating a doable increase. If a reduction is necessary, a level of $150 M in 2005 would be our recommendation, but what should be eliminated from the above would require a review of all priorities. In all cases, we are recommending new monies, not a transfer. Also, we have concentrated on the levels to be achieved by 2005. To reach these levels efficiently will require a ramp up beginning in earlier years. The committee is not endorsing any particular funding levels in the out years. The funding levels identified in the report are provided only to assist decision makers in developing long range budget projections.

The above does not include the system development costs associated with a revitalized space nuclear power program. A program designed to achieve the ambitious long-term system development goals identified in this report is estimated to cost be $170 M in 2005, but is based upon a set of national policy decisions. Hence, here it is treated separately. A national policy decision on human exploration missions will have a major effect on the need for advanced space nuclear systems. However, future deep space and robotic planetary missions are likely to drive the need for system improvements that are dependent upon new advances in technology. Current funding for mission specific system development efforts are provided by the mission sponsoring agencies. Consideration should be given at least to establishing a sustained level of R&D for this technology area apart from current generation or future system development efforts and facility infrastructure costs. An annual base technology R&D funding level of $25M for space nuclear technology, separate from the more costly full system development goals that dominate the $170M estimate, is listed above. This $25 M is directed at maturing technologies to the point where they may result in improvements to current generation systems or be incorporated into new system development programs having reduced technology development risk.

We strongly urge that funding be included in the budgets to reach the level of $240 million in 2005. This would be a wise investment for the future. The key products will be a strengthened existing nuclear plant fleet, more economic Generation III plant designs and construction capability for near term expanded nuclear power capacity in the U.S. and overseas, a prototype design for a Generation IV reactor, a stable, fairly broad availability of isotopes, the basis for electric and propulsion space systems, and a basic research program in place over a broad range of disciplines from which new ideas can flow.

Nuclear Energy Research Advisory Committee
(NERAC)
Subcommittee on
Long-Term Planning for Nuclear Energy Research

Long-Term Nuclear Technology Research and Development Plan

June 2000

Table of Contents

Appendices:

ACKNOWLEDGEMENT

The following Nuclear Energy Research Advisory Committee (NERAC) committee members and Department of Energy managers actively participated and took lead roles in the development of this long-term nuclear technology research and development plan:

John Ahearne, Subcommittee Chairman	Sigma Xi
Thomas B. Cochran	Natural Resources Defense Council
Joseph R. Comfort	Arizona State University
Allen G. Croff	Oak Ridge National Laboratory
Marvin S. Fertel	Nuclear Energy Institute
Robert Gottschall	U.S. Department of Energy, Office of Science
Beverly K. Hartline	Los Alamos National Laboratory
John Herczeg	U.S. Department of Energy, Office of Nuclear Energy
John J. Taylor	Electric Power Research Institute, Retired
Neil E. Todreas	Massachusetts Institute of Technology

I. INTRODUCTION

This document constitutes the first edition of a long-term research and development (R&D) plan for nuclear technology in the United States. The federally-sponsored nuclear technology programs of the United States are almost exclusively the province of the U.S. Department of Energy (DOE). The nuclear energy areas in DOE include, but are not limited to, R&D related to power reactors and the responsibility for the waste management system for final disposition of the spent fuel resulting from nuclear power reactors. Although a major use of nuclear technology is to supply energy for electricity production, the DOE has far broader roles regarding nuclear technology, many of which are not market-oriented.

DOE provides user facilities, such as research reactors and test loops, with provisions for inserting samples under known (controlled and measurable) parameters, and other research instruments or machines that are not commonly available but may be needed by the civilian and national security research communities. DOE has a role in ensuring isotopes are available as needed by the medical community. DOE is responsible for insuring that power and heat sources are provided to support the National Aeronautics and Space Administration’s (NASA) deep space and planetary explorations.

Lead responsibility for nuclear defense, safeguards and nonproliferation, environmental management and waste cleanup, and Navy nuclear propulsion systems development resides outside the Office of Nuclear Energy, Science and Technology (NE). However, nuclear R&D conducted in these other Offices may provide opportunities for leveraged collaboration with NE for cleaning up the wastes from the decades of nuclear weapons related activities at DOE sites; and for providing technical support of U.S. bi-partisan global nuclear policies to assure acceptable international practices in nuclear power plant safety, radioactive waste management, and proliferation resistance. The Department has a lead role in insuring that excess nuclear weapons material is safeguarded and, in a joint program with Russia, that such material is made much less accessible. And, of course, the DOE provides stewardship for the nation’s nuclear weapons stockpile and for the development of nuclear power systems for the U.S. Navy. This R&D plan does not address these national defense areas nor the program for the final disposition of spent fuel at a geologic repository, the lead responsibility for which is carried by DOE organizations other than NE.

In 1998, DOE established the Nuclear Energy Research Advisory Committee (NERAC) to provide advice to the Secretary and to the Director, Office of Nuclear Energy, Science, and Technology (NE) on the broad range of non-defense DOE nuclear technology programs. The NERAC recommended developing a long-range R&D program. This R&D plan is a result of that recommendation and is the first of what is expected to be an iterated series of long-range plans for nuclear energy in the Department of Energy. It will be desirable to update, expand, and refine this plan every few years.

The focus here is not on next year's budget. Rather, the focus is on what is necessary to develop over the next 10-20 years. Although this plan is intended to focus comprehensively on DOE's non-defense nuclear technology, it excludes some aspects of DOE's non-defense nuclear technology programs that do not involve R&D, e.g., landlord at sites and nuclear technology R&D activities that are being addressed by other advisory reports, e.g., accelerator transmutation of waste (ATW). However, this plan does include some closely related nuclear technology activities that have defense or national security implications.

DOE's nuclear technology mission is to serve as the federally responsible agent. Within this overall responsibility, DOE-NE has a mission to create and advance nuclear technology and infrastructure for non-defense and closely related defense applications. The DOE-NE mission leads to the following areas of responsibility:

- Enhancing nuclear power‘s viability as part of the US energy portfolio.[1] The issues for this R&D plan are what elements of nuclear energy should be supported and at what level.
- Providing the technical framework to implement US nuclear policies in support of national and global security.
- Supporting selected other missions, such as assuring a supply of medical isotopes and of space power systems.
- Maintaining sufficient U.S. expertise to assure an effective role in the international community and to support the needs for nuclear expertise to meet DOE defense and environmental missions.
- Sponsoring needed R&D and coordinating this work with other agencies.
- Maintaining necessary national laboratory and university nuclear infrastructure and supporting the education system.

Fulfilling the above also requires that DOE-NE undertake additional "cross-cutting" roles such as supporting broadly based research programs to advance nuclear technology.

In many respects, DOE-NE's role is to support and to catalyze research that, if successful, will be scaled up or applied by others, such as the nuclear power industry, NASA, or the medical-isotope suppliers. DOE-NE's focus should be on planning and sponsoring research and helping identify, plan, and broker with other sponsors to pursue promising results. When a concept is ready for the prototype or demonstration facility stage, DOE-NE should help transition the concept to whoever will implement or commercialize the results. A government-industry partnership, leveraged with substantial international participation, is the most appropriate way to undertake the major development and demonstration of advanced nuclear technologies.

However, the original research will have to be funded by DOE: a public agency must support such research because of what follows from the economic theory of market failure. “Markets cannot correctly allocate resources in the production of science, primarily because basic (unpatentable) science cannot financially reward the producer. Further, development based on

---

[1] As has been pointed out by many studies, including the 1997 President’s Committee of Advisors on Science and Technology (PCAST) study on Federal R&D, the DOE should support a portfolio of energy supplies. Such a portfolio should include nuclear energy, and this is recognized in the 1998 DOE Comprehensive National Energy Strategy. Some critics, however, contend that nuclear power is a mature industry whose role in the U.S. energy future should be determined by the market, without government involvement.

basic research might not be done at socially optimal levels because of the risks associated with a private party undertaking costly development."[2]

Nuclear Power. From a global perspective, it is clear that substantial increases in the demand for total energy, and electricity in particular, will occur over the next several decades, especially in the developing countries. Although the importance of nuclear energy may increase because of a combination of long-term conventional fuel supply constraints and environmental stewardship considerations, the worldwide future of nuclear power remains uncertain. For worldwide capacity, assumption-driven scenario forecasts vary widely. The joint International Institute for Applied Systems Analysis (IIASA)/World Energy Congress (WEC) *Global Energy Perspectives to 2050 and Beyond* examines six scenarios, with forecasts of worldwide nuclear power generating capacity ranging from 1900 GWe (a 440 % increase) in 2050 to 380 GWe (an 8 % increase) in 2050, as compared to the capacity at the end of 1999 of 352 GWe.

The Energy Information Administration (EIA) *Annual Energy Outlook 2000* forecasts a significant decline in U.S. nuclear generating capacity. The EIA notes that for nuclear capacity in 2020 to be the same as in 1998 would require every nuclear plant to get a license extension. Yet, substantial improvements in reliability and cost of operation and the timely approval by the Nuclear Regulatory Commission of the first license renewal indicate that any early decline in nuclear power operating capacity may be modest.

"Today it is not clear how and by which technologies the current problems facing nuclear energy may be resolved. What actually happens will depend on how safety, waste disposal, and proliferation concerns are resolved, and whether the greenhouse debate adds increasing importance to nuclear energy's 'carbon benignness.'" *Global Energy Perspectives to 2050 and Beyond*, p. 62.

Whether the world can successfully control both type and level of greenhouse gas emissions and any consequent global climate effects will depend primarily on the rate of increased use of non-emitting technologies and on energy demand growth in the developing world, particularly on those countries with major coal resources. Nuclear power has been an important contributor in reducing greenhouse gas emissions in the United States, in Asia, and in Europe, especially in France. How much of a contribution nuclear power can make in the future depends on the economic competitiveness of new plants.

"Most of the avoided carbon dioxide emissions over the last 20 years have come from nuclear power. In the USA today, on an annual basis, nuclear power avoids greenhouse gas emissions equivalent to burning 50,000 railroad cars full of coal." Undersecretary of Energy Ernest Moniz, "Shaping the Nuclear Future", 1999 Uranium Institute Annual International Symposium.

In the United States nuclear power is a major source of electricity generation and will remain so for many decades. The use of nuclear power also has significant global security implications that the U.S. government has addressed by policies fostering international protocols and standards for

---

[2] Personal communication from Prof. G. Rothwell, Stanford University Dept. of Economics, 24 March 2000.

nuclear safety, radioactive waste management, and non-proliferation. All these require U.S. technical leadership.

Isotopes. Radioactive and enriched stable isotopes, including radiation sources such as neutrons from reactors or x-ray generators, are essential for several critical areas of national importance to health, safety, national security, and industrial development and international competitiveness. These include the following:

- Medical applications: Diagnosis and therapy of a range of diseases relies upon isotopes, both applied directly for treatment and for diagnosis.

- Industrial usage: There are numerous vital applications of isotopes, including industrial radiography, measurements of chemical, elemental, or physical parameters of samples and bulk materials, thickness gauging, runway safety lights, smoke detectors, initiating chemical reactions, and sterilization.

- Research: Research relating to medicine, industry, agriculture, and the natural and physical sciences uses isotopes as tracers or as external radiation sources. Examples include biomedical research, materials testing, the environmental transportation of isotopes, and others.

- Federal programs: Isotopes are needed to support the work of government agencies, primarily related to national security applications.

The demand for radioactive isotopes and radiation sources used in medical applications, industrial and agricultural production, food safety, and as a research tool will continue to increase as the world's population approaches 10 billion and as new applications are identified. However, meeting this demand faces several major challenges, including (1) institutional complexity, (2) difficulty in measuring economics and benefits, (3) lack of central leadership, (4) public perception of risks, benefits, and reliability, (5) maintenance of technical expertise, (6) deteriorating infrastructure and, perhaps most importantly, (7) support for research to improve existing and to develop new applications.

Space Power Systems. Space power systems are needed for extra-terrestrial activities such as space exploration and communications. DOE-NE has an important role in providing radioisotope power systems, including the Pu-238 used to fuel such systems, conventional and advanced hardware used to convert decay energy to electricity, and, in the future, may provide reactor-based space power systems for situations requiring larger amounts of power. Radioisotope-based power systems face many of the same challenges as for other isotopes. Reactor-based systems require development of very advanced concepts to provide the required power with minimal weight and extraordinary reliability.

Education and Training. Perhaps the most important role for DOE-NE in the nuclear energy area is to insure the education system and the facility infrastructure are in good health. This research plan identifies important research topics whose funding can improve the potential for and the use of nuclear energy by the United States. But without adequate facilities and a sufficient number of qualified researchers, the research will not be done. Without a continued supply of new graduates in nuclear technology related areas, it will be a major challenge to continue to provide society with the benefits associated with the many applications of nuclear energy.

> "…both the nuclear energy future and nuclear materials stockpile stewardship depend upon the human resource base, new concepts growing from research, and the existence of a nuclear infrastructure that permits development and demonstration of everything from new fuel cycles to advanced materials. We have significant concerns in all these areas, in no small part driven by the uncertain nuclear energy future."
> Moniz, *op cit.*

Because nuclear technology applications – commercial nuclear power, radioisotopes for medical use, national defense needs, non-proliferation, national security policy implementation, space exploration, radioactive waste management, etc. – will continue to play an important role in the United States, it is important that the United States maintain a strong commitment to the education and training of nuclear engineers and scientists to support a wide range of nuclear activities. In support of all these roles, one of DOE-NE's primary responsibilities is to assure the country has the supply of nuclear engineers and scientists who will be needed to provide worldwide leadership in scientific, nonproliferation, commercial, and other uses of nuclear science, technology, and materials. This leads to the need to support undergraduate and graduate students, faculty, and both university and DOE infrastructure as well as to fund long-term nuclear-related R&D that is in the national interest. Support of nuclear technology also requires a cadre of experts trained in the handling of nuclear materials and the operation of nuclear facilities such as reactors, accelerators, and hot cells. This leads to the need for on-the-job training of operators at operating facilities on a continuing basis.

Nuclear expertise and nuclear engineering programs in U.S. universities are disappearing. The remaining expertise and programs are at risk of following in the next decade, or less. Without concerted action by DOE, supported by the Office of Management and Budget (OMB) and the Congress, most of the existing nuclear engineering programs soon will evaporate or be absorbed and diffused in other engineering disciplines. While cross-over from other engineering and science disciplines will be necessary and healthy, in the long term, educated nuclear engineers and scientists will be necessary to meet the needs described in this plan. Direct support to researchers at academic institutions is needed, in addition to support provided through projects run by industry or the national laboratories, valuable as these have been and will continue to be.

Nuclear Infrastructure. Nuclear infrastructure includes both the expertise and the facilities needed to advance nuclear technology for power, isotope, and education applications. These are facilities such as research and test reactors, various types of hot cells, accelerators, and supporting facilities such as those that exist at DOE national laboratories, universities, and in the private sector. They are typically multi-purpose (and multi-sponsor) facilities used to perform research, educate and train nuclear experts, and produce non-commercial isotopes.

Cross-Cutting Research. The long-term goal for nuclear technology R&D is to provide the knowledge base for maximizing the benefits to society of economical, safe, reliable, and proliferation-resistant civilian uses of atomic nuclei. Current vital applications include fission power, power generation for space missions, food safety, and medical and research uses of isotopes. DOE-NE's role is to sponsor R&D with significant societal benefits that will not happen without government involvement due to risk, long-time horizon, or inadequate short-term economic benefit for a commercial sponsor. DOE-NE's research program should be broad enough to welcome innovative but sound nuclear technology proposals relating to other promising nuclear applications that might be conceived in the future, and that are not covered by other federal programs.[3]

The President's Committee of Advisors on Science and Technology (PCAST) report on Federal Energy Research and Development for the Challenges of the Twenty First Century (November 1997) recommended that the Department of Energy establish two new nuclear energy research programs to maintain the option for nuclear power in the future. PCAST recommended the establishment of the Nuclear Energy Research Initiative (NERI), to support new and innovative scientific and engineering research. In FY 1999, the Department received over 300 research proposals and used a formal peer-review process to select 46 for funding. NERI topics of high potential interest to this report include direct energy conversion, new reactor designs with ultra long life cores, and advanced fuels with increased proliferation resistance. In FY 2000, the DOE-NE funded the proposals continued from FY 1999 and DOE is in the process of making additional awards. Funding levels are $19M, $22.5M, and $35M (proposed) for fiscal years 1999, 2000, and 2001, respectively.

NERI is a research program aimed at incubating new ideas while helping to arrest the decline of nuclear energy researchers. Research areas are identified in a request for proposals from academia, national laboratories, and industry, with collaboration encouraged. Awards are based on merit, judged by peer review. While addressing important topics, NERI can revitalize nuclear energy departments, retain high quality researchers in academia, national laboratories, and industry, and encourage and support the students who will be the base for the future use of nuclear energy in all its applications. This R&D plan builds on the NERI concept, adding more areas and more details for future calls for proposals, as well as identifying some specific, long-term programs that will require stable funding to achieve success.

The NERI program has been funded at levels substantially below what PCAST recommended. For many of the areas described in this R&D plan, a substantial portion of the new monies could be allocated for a NERI approach, where competitive proposals are solicited from the broad community, to elicit high risk, creative ideas. Not only would this increase the probability of accelerated progress, it would engender enthusiasm among faculty and students, bringing vitality back to the field.

PCAST also recommended the establishment of a program to address the efficiency of current operating reactors, referred to as the Nuclear Plant Optimization Program (NEPO). The NEPO program provides for joint research with industry, specifically, the Electric Power Research Institute (EPRI). EPRI provides a cost share of a minimum of 50%, and provides industry experts to select the highest priority tasks and to review results. Key areas of research include

---

[3] For example, civilian application of fusion research is the subject of a dedicated DOE program in the Office of Science. Coordination between DOE-NE and the fusion program is encouraged, but NE should not focus on fusion.

advanced instrumentation and control, steam generator non-destructive testing, and materials research. At the time of this report, NEPO projects have been selected and are in the final stages of funding and beginning work. Funding levels are $5M for fiscal year 2000 and a DOE budget proposal of $5M for 2001.

In addition to working with industry to coordinate research, DOE-NE should coordinate its efforts with those of the Nuclear Regulatory Commission (NRC), where appropriate.

International Collaboration. Many other countries are actively pursuing one or more facets of nuclear technology to meet their national goals. Collaboration with these countries can help meet a number of U.S. goals, such as increasing the cost-effectiveness of U.S. investments in nuclear technology; improving nuclear safety; reducing the environmental impacts from application of nuclear technology; strengthening proliferation resistance; and providing a means to remain involved and aware for the purpose of encouraging the pursuit of desirable nuclear technology. Some critics note that, in spite of substantial efforts by the United States and many countries, international collaboration among some countries has led to proliferation of nuclear weapons efforts, in some cases successful.

Report Organization. This plan is divided into the following sections: basic science and engineering; power reactors; isotopes and other radiation sources; space systems; implications on the NE programs of other key nuclear energy missions; international aspects; funding; and general comments. The section on power reactors has three subsections: advanced fuel cycles; instrumentation, controls, modeling, simulation, probabilistic risk assessment, human factors, and organizational performance; and reactor technology and economics. This plan is based upon two workshops, attended by more than one hundred members of the nuclear community. The workshops were divided into eight breakout groups. The reports from those groups are included as appendices. In addition, comments were considered that were generated by notices in journals, at professional meetings, on the NERAC web site, and from letters sent to many members of the nuclear community. Drafts of this plan were circulated for comment to all workshop attendees.

NERAC has other subcommittees working on education and infrastructure and a task force to identify technological opportunities for increasing the proliferation resistance of global civilian nuclear power systems. This report does identify some needs in these areas. These are not meant to be inclusive, since the subcommittee and task force reports will provide that level of detail.

II. BASIC SCIENCE AND ENGINEERING RESEARCH

> "Even though one cannot anticipate the answers in basic research, the return on the public's investment can be maximized through long-range planning of the most promising avenues to explore and the resources needed to explore them." (p. v) "Pursuit of this goal entails developing new technologies and advanced facilities, educating young scientists, training a technical workforce, and contributing to the broader science and technology enterprise." (p. vi)
> "Nuclear Science: A Long Range Plan", DOE/National Science Foundation, Feb. 1996.

Although nuclear power has been developed for over 40 years, many technical issues remain. Research on these issues is needed for continued safety, improved economics and a deeper understanding of how new knowledge can contribute to the future of nuclear power. This section addresses basic research. Subsequent sections cover applied research.

Today's reactors, which are based largely on 1970's technologies, operate under close supervision in a conservative regulatory environment. Although the knowledge base is adequate for these purposes, significant improvements in our knowledge and reduction of the inherent uncertainties could bring substantial cost savings in current reactor operations and reduced costs for future reactors. Furthermore, they could enable innovative designs that reduce the need for excessively conservative and costly factors of safety, and lead to improved efficiencies, superior performance, enhanced safety and reliability, and significant extensions in safe operating lifetimes. Future reactor technologies are likely to involve higher operating temperatures, advanced fuels, higher fuel burnup, longer plant lifetimes, different materials for claddings and containment vessels, and alternative coolants. To implement such features, substantial research in fundamental science and engineering must be carried out to supplement applied research specific to individual promising design concepts. Such fundamental research need not and should not be directed to any specific design. Although motivated in part by the need for new nuclear reactor system designs, the research also would have far-reaching impact elsewhere in engineering and technology.

Five broad topics have been identified for extending current research into new frontiers:

(1) the environmental effects on materials, in particular the effects of the radiation, chemical and thermal environments, and aging;
(2) thermal fluids, including multiphase fluid dynamics and fluid-structure interactions;
(3) the mechanical behavior of materials, including fracture mechanics, creep, and fatigue;
(4) advanced materials, processes, and diagnostics; and
(5) reactor physics.

Applications would extend to stress and aqueous corrosion, high-temperature gas corrosion, welding and joining, pressure vessel embrittlement, advanced fuels and new coolants, the degradation of radioactive waste packages, and the non-destructive evaluation and monitoring of reactor conditions. Many of the applications will require knowledge from more than one of the topic areas.

A key element of such research is the development of reliable predictive models and computational codes for simulating the conditions inside reactor systems. Predictive models at the continuum scale must be based on rigorous fundamentals and will require multiscale computing. In addition, substantial experimental work is required to provide the data bases needed for testing and validating the models and codes. Specific issues and applications for the research are given in the following sections.

Environmental Effects on Materials

The high-radiation fields, high temperatures, and corrosive environments in a nuclear reactor or other complex nuclear system (e.g., an ATW system) can accelerate the degradation of nuclear fuels, component materials, material interfaces, and joints between materials (e.g., welds) during individual-component or plant lifetimes. Likewise, the high-radiation fields and corrosive environments of a geologic repository can accelerate the degradation of nuclear waste packages over much longer time scales. Radiation effects in materials can cause embrittlement, dimensional changes, cracking, and accelerated corrosion. Radiolysis within the reactor coolant (or ground water for a repository) and inadequate control of water chemistry can exacerbate these degradation mechanisms and lead to anomalous material deposition. A fundamental understanding of radiation effects, radiochemistry, and corrosion in a reactor environment and elsewhere in the nuclear fuel cycle is needed to ensure successful life extension in current reactors, to improve the efficiency, reliability, performance and economics of current and future reactors, and to develop acceptable solutions for the disposition of spent nuclear fuel.

Although much work has been done on the fundamentals of radiation effects in simple alloys, particularly on elemental metals in the 1960's and 1970's and on model binary alloys in the 1980's and 1990's, radiation effects in engineering steels, advanced ceramics or composites, and nuclear fuels at high burnup are not well understood. The current state of knowledge falls far short of being able to formulate reliable predictive models of performance in reactor and repository environments. Currently, there are only a few limited studies of fundamental radiation effects in alloys and ceramics, irradiation-assisted stress corrosion cracking, radiation effects in the target/blanket module for accelerator-based neutron sources, and environmental effects on nuclear waste package components.

The development of a fundamental understanding as well as predictive models of radiation effects on the structure, properties, and corrosion behavior of materials over a range of temperatures, radiation doses (or burnup), and time scales represents the broadest category of research needed. Radiation effects include enhanced diffusion, phase transformations, restructuring (as in the rim effect), loss of mechanical integrity (such as embrittlement), accelerated corrosion, significant swelling, and decreased thermal conductivity. Such research should include materials relevant for advanced nuclear fuels, cladding, structural components, containment vessels, and nuclear waste packages.

Advanced multi-scale computational techniques are also required along with additional experimental programs. Successful simulation models will integrate *ab initio* calculations with atomic-level simulations of radiation-damage processes, and scale up the physics of radiation-damage processes to macroscopic and continuum simulations that predict microstructural evolution, phase changes, restructuring, mechanical properties, and corrosion behavior. The experimental programs will support and validate the computational techniques, and must themselves be supported with radiation testing and analysis facilities.

Joining technologies and the effects of radiation on joined components form a special category within environmental effects. Advances in understanding irradiation-assisted stress corrosion cracking require research in radiation materials science, and more generally on the fundamentals of grain boundary behavior, corrosion, and localized deformation and fracture.

Reactor coolant properties and behavior can be significantly impacted by radiolysis and need further study, particularly in conjunction with studies on radiation effects in the materials in contact or potential contact with the coolant. In addition, wide opportunities for research exist into the thermophysical properties and behavior of alternative liquid and gaseous coolants. A fundamental understanding and predictive models of radiation-induced degradation mechanisms and corrosion of nuclear waste packages must be developed if performance is to be predicted over thousands of years with confidence.

Accelerated irradiation testing is generally required to characterize a material's response to radiation, expected plant lifetimes, or waste-package storage times. Such accelerated studies add an uncertainty because the damage rate is much higher than in the actual environment. Thus, few data are acquired at actual reactor (or waste package) conditions. Therefore, research must be very forward-looking, and it needs to begin now for the materials’ behavior or fuel performance information needed in 10 to 20 years. Sufficient time is needed to irradiate and test materials and fuels to establish an adequate database for design evaluation and regulatory assessment. Unfortunately, the research reactors that can support these irradiation studies are diminishing rapidly in capability and number.

Thermal Fluids

The ability to model accurately fluid-flow and heat-transfer phenomena related to reactor thermal performance is vital for understanding the margins of safety in any nuclear reactor facility. In some cases, continued improvement in the analytical tools for design-basis accidents already has resulted in eliminating these events from establishing limiting conditions (e.g., peak fuel rod power, power shape, etc.) for normal operation in currently operating water reactors. This trend is expected to continue as more utilities turn to so-called "best-estimate LOCA" codes. As a result, transient events and local thermal-fluid (TF) conditions will likely establish the principal conditions for limiting operations. This situation is expected to be true for future water reactor designs as well. For other reactor types (such as liquid-metal or gas-cooled reactors), local TF models are essential for analyzing core performance. Improvements in smaller-scale, local TF models (e.g., for sub-channel models and computational fluid dynamics models that include two-phase, supercritical, and other flows) could lead to improved economics in plant operations.

Computational and multiphase fluid dynamics techniques are needed which accurately model fluid flow and heat transfer on all time and space scales. Research is needed to improve both multiphase and single-phase fluid dynamics models. These techniques would range from small-scale simulations of localized effects, such as boiling, to large-scale full plant simulations. Additionally, extrapolation of bench-scale experimental results to larger reactor systems is a challenge, particularly when only smaller and intermediate-size facilities are available. The simulations also need to correctly model the coupling of the different scales in normal, transient, and accident conditions. With continuously improving computational capabilities, such as with parallel supercomputing, it is becoming feasible to incorporate first-principles phenomenology, integrate all the relevant physics and engineering, couple between micro-scale and macro-scale processes, and simulate plant behavior in real time (or faster). These models have the potential of replacing the less fundamentally based safety codes in current use.

A reliable and broad database of thermal-fluid experiments is critically important for developing and benchmarking improved and new thermal-fluid models. The existing body of experimental knowledge must be preserved and its quality verified. In some cases, the existing data are adequate. In others, they are not and new experiments will be necessary. Pertinent examples include new coolants or extended ranges of operating performance (i.e., for supercritical flows, for direct-contact heat transfer, and for superheated coolants.) Furthermore, new reactor designs introduce compatibility issues between coolant and structures that can lead to adverse fluid-structure interactions, particularly in the presence of chemical and multiphase environments and in harsh radiation conditions. These radiochemically-enhanced interactions in sub-cooled boiling can yield degradation through corrosion and in the thermal performance of affected components, e.g., fuel assembles. Such phenomena challenge current experimental sensing and measurement capabilities and can limit the licensed system performance. Cases of anomalous material deposition and the axial offset anomaly in many pressurized water reactor (PWR) systems worldwide are examples of such limitations.

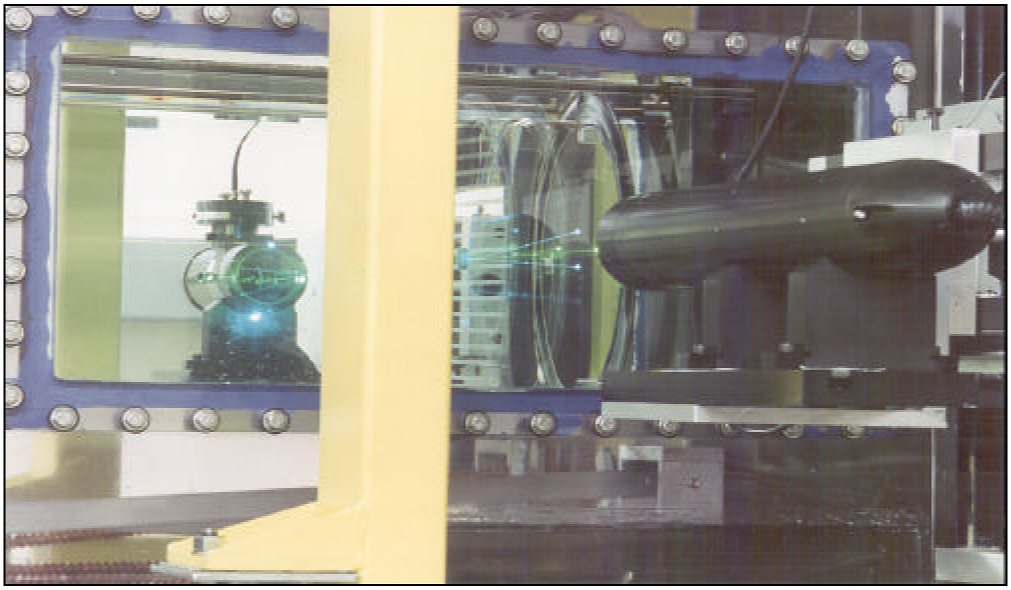


Figure 1. Laser doppler velocimetry apparatus used at Idaho National Engineering and Environmental Laboratory to study thermal fluid physics of high temperature flows in advanced reactors systems under an ongoing NERI Project.

Mechanical Behavior of Materials

The loss of fracture toughness (i.e., embrittlement) and ductility, along with the deleterious effects of creep, fatigue, swelling, and stress relaxation, are of critical importance to the safety, lifetime, and economic performance of nuclear power reactors. Improvements in fundamental understanding of mechanical behavior, both through carefully controlled experiments and theoretical modeling, are necessary for better predictions of component performance. Another important objective for research into mechanical properties is to find and develop methods for incorporating probabilistic predictions into codes for use by the NRC in its transition to risk-informed regulation.

No current unified model successfully explains either deformation or fracture on all length scales. Dislocation theory has achieved some success on a microscopic scale; continuum elasticity and constitutive equations have achieved success at macroscopic lengths. What is lacking is a unified model that can effectively incorporate aspects of both dislocation theory and elastic-plastic continuum models at the critical interval lying typically between 0.1 and 10 microns, where these otherwise successful models do not converge. Note that this interval corresponds to the size regime of microstructural features that may be controlled by appropriate synthesis and processing parameters.

There is no first-principles understanding of fracture toughness and the brittle-ductile transition. The challenges are to develop a predictive model for calculating the fracture toughness a priori and to predict the temperature where a material transitions from brittle to ductile fracture. The information needed includes the resolution of technical issues that could be expected to save several million dollars per reactor-year by enabling costly cool-down and start-up procedures to be less conservative.

Materials research on the effects of impurities as well as alloying elements such as copper, nickel, and phosphorous has resulted in substantial improvements in the performance of ferritic pressure vessel steels. However, the physical mechanisms underlying these elemental effects are not understood mechanistically. Testing of surveillance specimens does not address the substantial effect of flux attenuation through the vessel thickness, the spatial variability of microstructure and properties over such large structures, the validity of embrittlement correlations, nor the characterization and behavioral effects of processing-induced banding and segregation. These issues require testing materials from decommissioned pressure vessels. Although enormous amounts of data have been accumulated under actual operating conditions in numerous reactors on various steels in myriad conditions, it is difficult to obtain insight from these data into the basic mechanisms of embrittlement without the purposeful control of variables that characterizes the materials science approach. Empirical correlations based upon such data inherently contain large uncertainties. Despite these shortcomings, there is a need to retain and preserve surveillance specimens.

The effects of irradiation times of up to 80 years require experiments and modeling which embrace (1) gathering and analysis of further statistical evidence for recent preliminary reports of increased embrittlement rates over long times; (2) development of reliable predictive models based on an understanding of the mechanisms responsible for microstructural development; and (3) understanding the interplay between long-term thermal aging phenomena and radiation effects.

There is a strong need for detailed knowledge of the structure and composition of both the matrix defects and copper-containing precipitates that underlie embrittlement. There generally exists a wide range of precipitates and clusters, some of which are only loose correlations of atoms, which do not fit the description of precipitates in the usual metallurgical sense. Knowledge of the degree of co-segregation of additional solutes (e.g., P, Mn, Ni, and Si) to these extended defects, as well as knowledge of their interactions with mobile dislocation segments, is also required before improved predictive models of irradiation-induced mechanical property changes can be constructed.

Computer simulation is now nearly as powerful as experiment and theory. The ability to simulate the microstructural features that are essential to performance will make it possible to understand the relationship between synthesis, processing, structure, and performance. Molecular dynamics simulations of cascade production, which provide information over atomic distances and picosecond time scales, currently suffer from inadequate interatomic potentials. The integration of multi-scale approaches on theoretical and experimental levels needs further development. The modeling methodologies range from molecular dynamics simulations at the atomic scale to global defect reaction-rate theory for predicting the evolution of microstructure and the concomitant effects on properties. Once the microstructural state of the material has been reproduced, further continuum-dynamics methods need to be integrated for predicting deformation and fracture behavior in the evolved microstructural state. In the development of such integrated multi-scale models, it is always crucial to "benchmark" computations and simulations against experimental measurements.

There is now an unprecedented opportunity to exploit emerging computational and analytical tools for the study of fundamental dislocation issues. These new tools include massively parallel computer codes, new techniques for establishing activation energies from atomistic calculations and for simplifying computations involving distributed dislocations (mesoscopic scale), and in-situ X-ray techniques for direct, real-time dislocation studies (densities, types, and patterning). The anticipated advances in understanding would span the length and time scales of individual dislocation motion, the intersection of grain boundaries by dislocations, the formation of dislocation networks (the patterning problem), and the deformation of polycrystals (work hardening).

There is a lack of understanding of the evolution of the defect state, microstructure, and microchemistry associated with below-yield cyclic stress. However, a solid subjected to such cyclical stress has a "memory" for its stress history, implying that there is associated cumulative damage. The challenges are to identify this damage, to find an experimental diagnostic, and to correlate this defect state with the remaining safe life before failure. Thermal striping (rapid-thermal-cycle-induced fatigue) of plant components has recently caused cracking and failure of piping in operating plants in Japan and France. One of the fundamental limitations in understanding thermal striping is calculating the rapidly changing fluid temperature at the material surface. Limitations of both the single-phase computational fluid dynamics turbulence models in handling simultaneous momentum transport and energy transport, and of the ability to calculate the behavior of the structure being thermally striped, prevent understanding and prediction of the material's performance.

Advanced Materials, Processes, and Diagnostics

National and international trends in nuclear fuel utilization are toward higher burnup, up to about 75 GWD/MTU or higher. Increased burnup and longer reactor cycles have very attractive economic features. In addition, extended burnup can lead to fewer fuel assemblies that must be stored on site and ultimately disposed of in a repository. Higher burnup also will lead to fewer assemblies per waste package, or even alternative approaches to disposition, such as partitioning and transmutation.

Longevity of reactor fuels has a major influence on operating economics. To achieve significant increases in average core burnup requires the development of advanced fuels based on either traditional fuel materials (e.g., UO_2 or UO_2-ThO_2), or advanced fuel materials or concepts (e.g., metallic fuels, carbide fuels, pure actinide fuels, or composite fuels including inert fuel matrices). The impact of higher burnups or new fuel materials on proliferation, disposal costs, and public safety may be significant.

Increasing demands are being placed on clad performance as the fuel burnup limits are being extended. Such extensions must be done with care because the cladding is the first barrier to the release of radioactive fission products to the reactor coolant system. In addition, envisioned burnup limits will require the development and qualification of new clad materials that meet

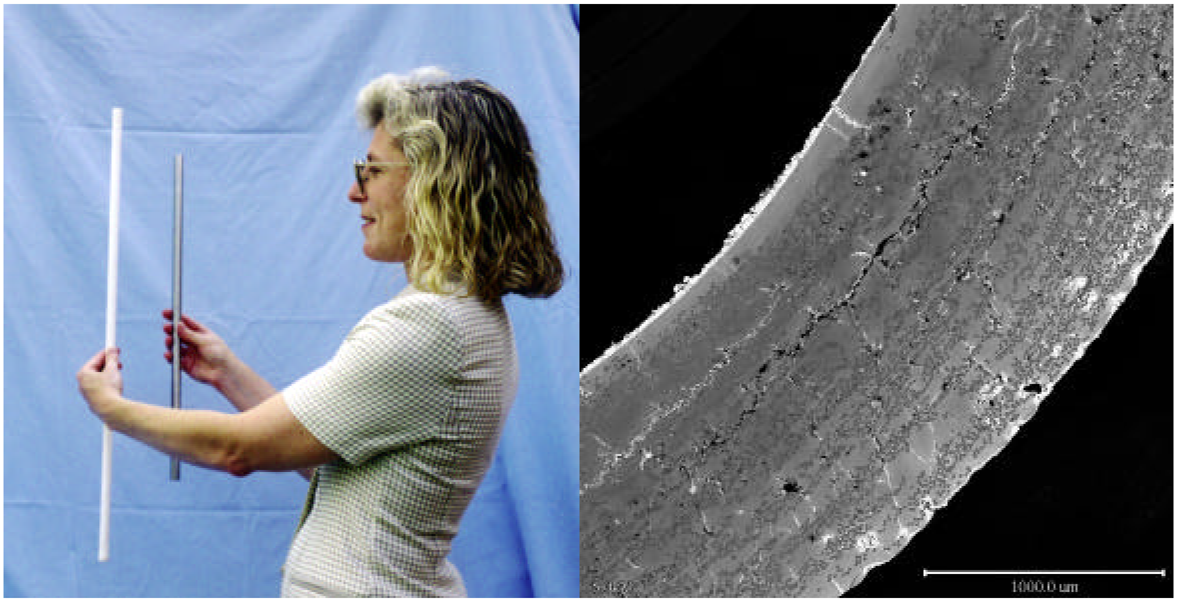


Figure 2. A new ceramic composite clad material is being evaluated by Gamma Engineering for potential nuclear applications under DOE's NERI Program. Left - NERI Project Manager Bonnie Packer holds a new ceramic tube and a traditional zircaloy clad tube used in commercial LWRs. Right – Microscopic cross-section of ceramic cladding tube.

higher performance criteria. Advanced reactor concepts that incorporate gas or liquid metal coolants, in addition to high burnup, will greatly challenge cladding performance.

Reliable welding and joining procedures are necessary for joining metals, ceramics, and dissimilar materials in general. This need pertains to the construction of future reactor systems and for the on-line repair or refurbishment of aging ones. Advancing new welding processes and developing new welding procedures can help prevent expensive power outages attributed to weld-related problems. Because a day of forced outage of a nuclear plant can cost up to $750,000, better welds can extend the lifetime of older components by decades and can save the industry billions of dollars. Welding represents 20% of plant maintenance costs. A good weld extends plant life, enhances safety and reliability, and cuts down on operation and maintenance costs. In some cases, welding may provide the only economically viable approach for avoiding a permanent plant shutdown.

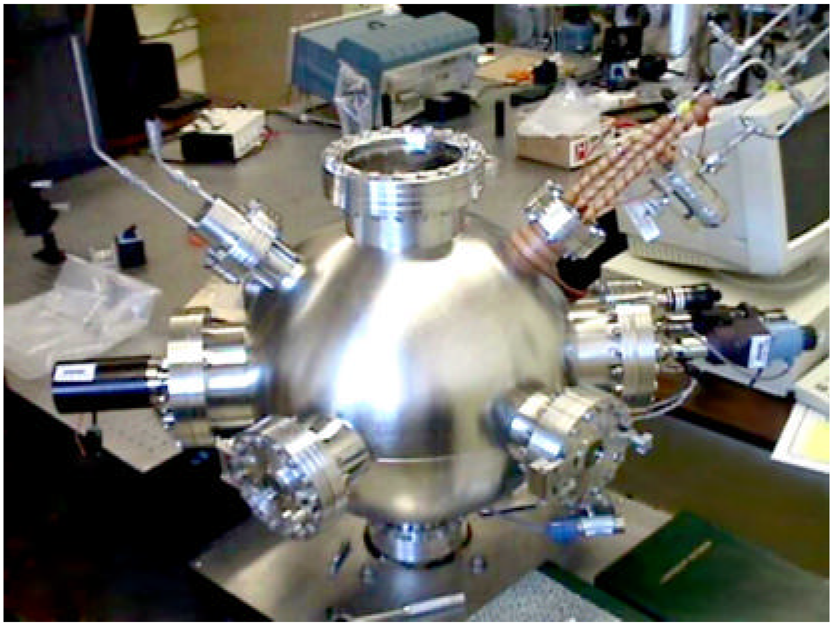
Non-destructive evaluation (NDE) has two very critical functions in the production of nuclear energy. One of these functions is to provide the highest possible quality assurance for the components that comprise a reactor and for periodic inspection during outages. Improvements in the speed, accuracy, resolution, and detectability limits of such techniques will lead to improvements in plant safety, operating efficiency, and the safe lifetime of components. A second function of NDE is to provide continuous condition monitoring, i.e., in-situ or on-line early warning of possible impending or catastrophic component failure, including the ability to predict the remaining safe lifetime for a component. The development of NDE techniques that can measure the degree of embrittlement of reactor pressure vessel steels caused by long time exposure to radiation would be a breakthrough for extending the life of existing pressure vessels.

There will be an increased opportunity in future reactor systems for condition monitoring (the continuous monitoring of flaws and/or materials properties). The development of appropriate sensors, based on sound physical principles, that can survive when continuously exposed to the hostile conditions of reactor environments, is an important research direction.

There currently exists a limited amount of research in each of the above areas. In the case of high burnup fuels and advanced fuel materials, research categories include fission gas release, restructuring of fuel (as in the “rim” effect), pellet-clad interaction and higher burnup at higher operating temperatures, and the capability to predict, test, and verify performance under both steady-state and transient conditions. For cladding, research categories include ceramic composites that have sufficient fracture toughness so as not to be vulnerable to brittle fracture, and fiber-reinforced ceramic cladding. In addition, greater understanding of phenomena such as corrosion, mechanical properties and behavior, radiation effects, phase behavior and thermodynamic performance, and fretting is needed. For welding and joining, broad research categories include laser welding, underwater welding, and temperbead repair welding.

Finally, for the case of NDE and condition monitoring, broad research categories include ultrasonic, electromagnetic (especially eddy current), and radiographic techniques invoking improved signal processing procedures to better discriminate between signals from flaws and those from benign geometrical discontinuities; algorithms that will produce probabilistic output; the correlation of acoustic harmonic generation with remaining time to fatigue failure; and sensors that can survive in the hostile reactor environment under temperature, radiation, and corrosion.

Figure 3. Laser Ablation Deposition Apparatus used at the University of Florida for ceramic corrosion protection systems for zircaloy cladding experiments under a NERI grant.



Reactor Physics

Advancements in reactor concept design can be expected to require additional data for basic nuclear properties, such as neutron and gamma spectral data, microscopic cross sections and resonance parameters, fission product yields, isotopic decay constants, and delayed neutron data. The resources available for the development of nuclear data information have been allowed to deteriorate in recent years. The existing database is only marginally adequate for present applications and is unlikely to be sufficient for future applications. A critical examination of the existing nuclear data resources by specialists in the field will need to be carried out with modern sensitivity analysis techniques to identify data needs in the context of contemporary and anticipated applications.

Nuclear data used in the analysis of nuclear reactor systems is generally obtained from the U.S. Evaluated Nuclear Data File (ENDF). Nuclear data specialists have generated ENDF by critically examining available experimental data and supplementing them with results from well-benchmarked theoretical calculations. Some specific nuclear data needs have already been demonstrated by this procedure. Among these are data for fission products in burnup-credit calculations, for Th-232 and U-233 in advanced systems involving the thorium cycle, for minor actinides involved in nuclear waste burning, for lead and bismuth coolants in advanced metal-cooled reactors, and for structural materials used in shielding applications.

Given the physical data and description of the reactor system, analysis methods must be applied to predict the attributes of a nuclear system. Normally, criticality constants, the flux, power, and burnup distributions, and reactivity feedback coefficients are the attributes of interest. To obtain them, the neutron transport equation or some approximate form of this equation (e.g., diffusion theory) must be solved. Challenging issues include detailed modeling of geometries, more efficient self-shielding algorithms, and efficient 3D pin-to-pin transport calculations. In addition, auxiliary models are required, such as those associated with isotopic depletion equations and delayed neutron equations. Exploitation of stochastic (Monte Carlo) methods with powerful computers is leading to greater modeling sophistication. Such methods can avoid most algorithmic simplifications used for deterministic methods.

Although computer power will continue to increase rapidly, it is unclear that current methods will be adequate for the core analysis of future reactors. To reduce the dimensionality of the problem for deterministic methods, a subregion of the core is generally analyzed with substantial energy and spatial detail to generate spatially homogenized, energy-averaged cross-sections. These cross sections are then utilized to analyze the total core by using a model with a coarse spatial mesh and a few energy groups. Many assumptions come to play in this approach, and some may not be applicable to future reactor designs. Stochastic methods must follow a very large number of randomly generated processes to obtain meaningful results. Parallel computer architectures, along with the associated parallel solution algorithms, can overcome these limitations and reduce the computational burden to acceptable levels. Another area where there will likely be a need for improvement is in the treatment of resonance phenomena in the unresolved and resolved regions. Interference effects due to resonances from other isotopes, spatial self-shielding, and energy self-shielding are difficult phenomena to model accurately.

Integral experiments will need to be conducted to assure that the nuclear database and analysis methods are sufficient for the design of prototypical and commercial cores within the required certainties of key core parameters. These experiments would involve fuel, coolant, clad, and materials in structures characteristic of advanced reactor designs. They should measure reaction-rate ratios and spatial distributions, reactivity coefficients, flux distributions, and criticality. In addition, attention needs to be focused on assessing the different forms of heterogeneity being introduced into these advanced designs. The capability of the United States to conduct such experiments is limited. Current facilities are under utilized and not well supported financially, while expert personnel are retiring or transferring into different fields, are generally poorly supported, and few new ones are attracted to nuclear energy R&D.

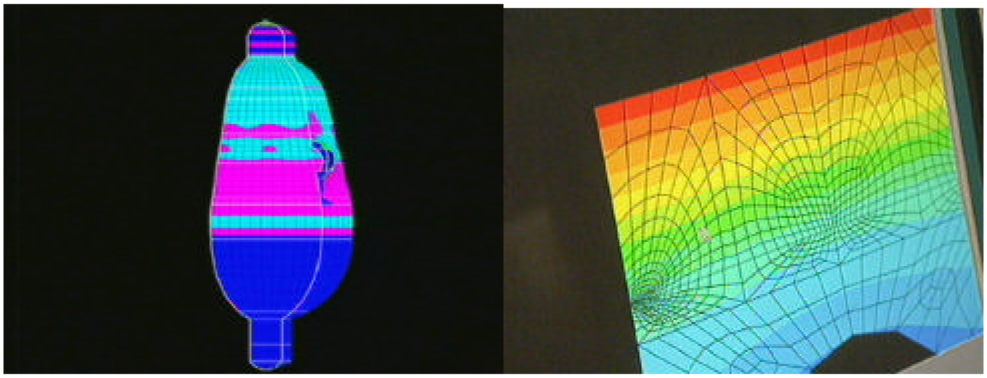


Figure 4. **Computational modeling techniques for structural stress analysis are demonstrated at Sandia National Laboratories.**

Funding

The fundamental research described in this chapter is long-term. Very little research that would have direct application to the issues identified here is currently being supported or conducted, although some broader activities potentially have some relevance. The topics can encompass many different program offices within DOE. It is estimated that a sustained program of *new* funding of about $54 million (M) per year is needed to accomplish the research described in this chapter. Additional capital funding for facilities is estimated to be about $6 M per year.

III. NUCLEAR POWER

Although there are disagreements as to how large the nuclear power share of US electricity generation will be in the next 30 years, it will remain a significant portion. The DOE Office of Nuclear Energy, Science and Technology (NE) has important strategic roles in the following three areas related to development of advanced and improvement of existing nuclear power systems:

(1) research on advanced reactor concepts with focus on concepts that show promise over existing designs in improved economics, safety, non-proliferation attributes, and waste characteristics;
(2) development of virtual construction capability, advanced information management, and risk-based safety methodology to achieve economic competitiveness in the U.S. market for Generation III reactor systems;
(3) development of processes and technologies, including new fuels, that can be utilized to improve the operating efficiency of existing domestic reactors; and
(4) development of systems with increased proliferation resistant fuels that can be utilized in existing foreign research reactors.

Barriers to Future Expansion of Nuclear Energy: economics, proliferation, safety, waste.

- New designs must remove long-term barriers to expansion of nuclear power and be competitive.
- New approaches required; technologies likely to be revolutionary.
- Cannot rely on carbon credits to make nuclear attractive.

William D. Magwood, IV, 8 December 1999

Research and development on advanced reactors will require, after a period of evaluation and screening of innovative concepts fostered in the NERI program, a substantial amount of experimentation, including extensive irradiation testing of advanced fuels. The promising concepts should be reviewed by the Nuclear Regulatory Commission and by prospective nuclear power plant owner-operators to evaluate licensability and operability. The licensing effort may require DOE funding to support reviews performed by the Nuclear Regulatory Commission. For efficiency improvements, DOE should focus on research, development, and demonstration for domestic reactors that would improve the efficiency and reliability of those plants through new operating related processes, technological advances, and fuel design improvements, including higher burn-up fuels, that can be used in existing PWRs and BWRs. Research and development of improved and higher burnup fuels for existing reactors must be accompanied by parallel efforts to ensure that these improved fuels can be licensed and utilized in a timely manner in reactors under existing and extended licenses.

"I, like most of my colleagues in the utility industry today, am largely focused on the short-term….None-the-less, I want to assure you that utility executives do care about the long-term future of this industry….There is no more important action for the future of nuclear power than operating our existing plants safely, reliably and efficiently and demonstrating that they can play an important, positive role in a fully competitive market….Although energy policy analysts and investors exhibit a growing confidence that existing nuclear plants can survive, and indeed thrive, in a competitive electricity market, they are not at all confident that new nuclear power station construction and licensing costs can be reduced to the point that capital will be attracted to these projects…New reactor designs that cannot demonstrate their ability to compete financially in the marketplace will not be built, pure and simple." (Emphasis in original.)

Greg Rueger, Chief Nuclear Officer, PG&E, and Chairman, EPRI Nuclear Power Council, 8 December 1999.

This report uses terms for categories of nuclear plants, defined as follows:

Generation I:	Prototype and demonstration plants built through the 1970's.
Generation II:	The existing fleet of Light Water Reactor (LWR) plants, except for the few Generation III plants already in operation.
Generation III:	Advanced LWR plants, both evolutionary and passive.
Generation IV:	Revolutionary advanced nuclear plant designs with a variety of fuels, coolants, moderators, and configurations.

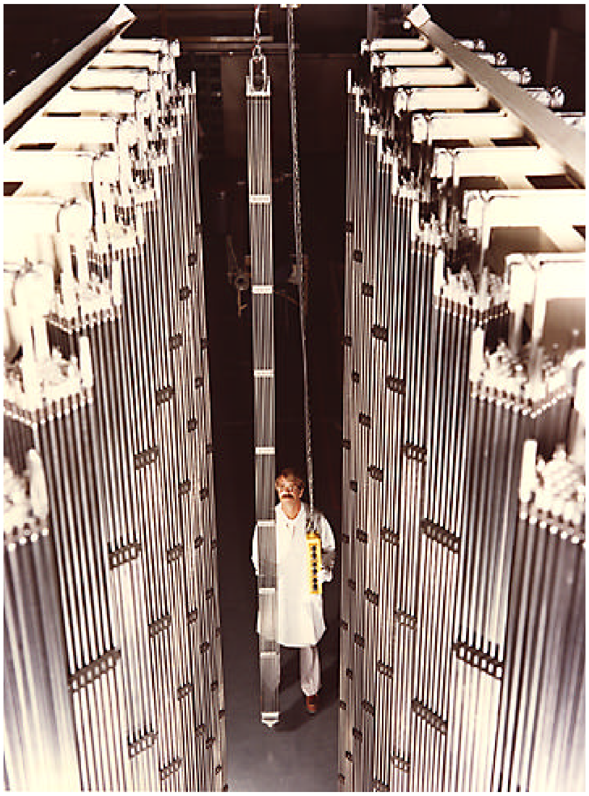


Figure 5. Typical pressurized water reactor fresh fuel assemblies

A. Advanced Fuel Cycles

The scope of research and development selected for the area of advanced fuel cycles encompasses the following three fuel cycles: uranium-based once through; uranium-based closed cycle (with emphasis on dry processing); and thorium-based fuel cycle. In each of these fuel cycles, R&D on surplus weapons materials (HEU and Pu) disposition should be considered.

The scope of R&D includes a variety of thermal and fast spectrum power reactor fuel forms, including ceramic, metal, hybrid (e.g., cermet, cercer), and liquid, as well as fuel types, including oxides, nitrides, carbides, and metallics.

Enabling technologies such as advanced cladding, water chemistry, and alternative moderators and coolants also should be considered. The fuel cycle research includes consideration of advanced enrichment technologies for fuel and burnable absorbers and considers the impact of fuel cycle options on the proliferation of nuclear weapon materials, waste generation, waste form, waste storage, and disposal. The R&D scope also includes development of higher density LEU (<20% U-235) fuels for research and development reactors.

In the near-term (5-10 years), a primary focus of the R&D is on achieving higher burnup fuel for existing and advanced light water reactor technology (generation II and generation III reactors) and higher density fuels for research and test reactors. Many areas of research should be pursued immediately regarding fuel form and fuel type performance for potential generation IV reactor concepts. Within five years, it is assumed the fuel cycle R&D would be fully integrated with any specific generation IV reactor designs emerging from the screening of NERI R&D innovative concepts.

The advanced fuel cycle R&D program can provide the following important enhancements:

1) strengthening the non-proliferation regime, e.g., higher density research reactor fuels will enable research reactors to achieve desired neutron fluxes without reliance on HEU (> 20% U-235) fuels;
2) improving the safety and reliability of nuclear fuel used in both current and next generation reactors;
3) reducing the quantity of nuclear waste resulting from reactor operations and possibly improving the characteristics of the waste produced by future reactors; and, most importantly,
4) reducing the cost of electricity produced by nuclear power plants.

Many US policy makers are increasingly interested in ensuring that nuclear fuel cycles are highly proliferation resistant. It is recognized that certain fresh-fuel compositions and longer in-reactor residence times (i.e., higher burnups) can each result in a spent fuel product that is even less attractive than existing spent fuel from the perspective of potential proliferants. Also, if new fuel designs offer improved economics and alleviate disposal issues, then incentives for reprocessing (i.e., separation of weapons-usable materials) may be reduced. This would further support US non-proliferation policy.

Improvements in the burnup for current fuel and in the design of new high burnup fuels for future reactors could increase the time between refueling outages and decrease the quantity of waste generated, both of which offset additional enrichment costs and thus may result in improving the economics of producing electricity. It should be noted that to obtain the reduced outage time benefits of high burnup fuel, further R&D in maintenance technology will be needed, and is recommended in Section III-C, to permit operation over long periods of time (> 2 years) without having to shut down for preventative maintenance of for forced maintenance outages.

While current R&D on advanced fuel designs is relatively limited, the work in progress is important and would be complimentary to a longer-term DOE initiated R&D program. Examples of some of the more relevant activities are highlighted below.

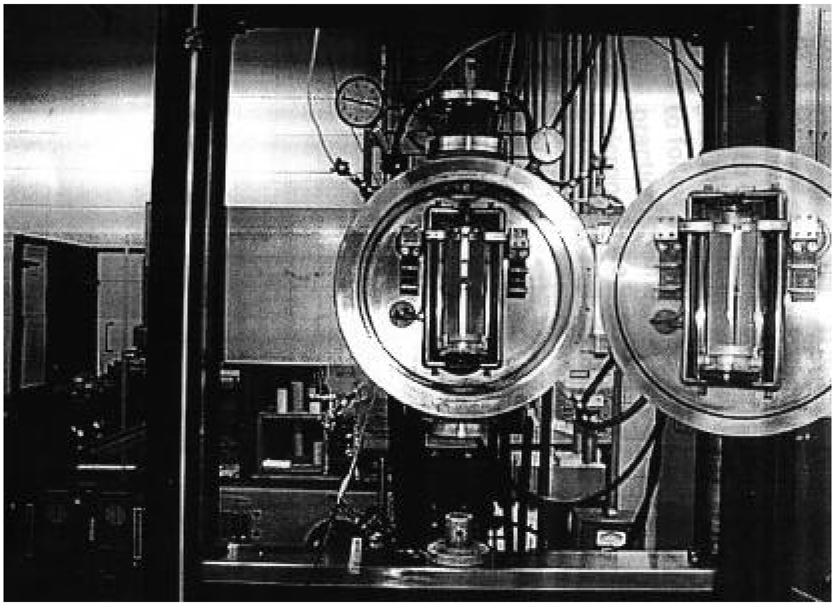


Figure 6. Purdue University sintering furnace; used for demonstrating advanced fuel fabrication techniques

In the United States, the Electric Power Research Institute (EPRI), in consultation with the Nuclear Regulatory Commission (NRC), is conducting a robust fuels research program intended to facilitate NRC approval for current fuel designs at modestly higher burnup in existing reactors. As part of the surplus weapons disposition program, both the United States and Russia are implementing research on the use of weapons plutonium in MOX fuel in once-through fuel cycles. France and Japan have ongoing R&D programs related to MOX fuel performance in reactors and uranium-free fuels for plutonium disposition. India continues to conduct research on the thorium fuel cycle. The United States, Russia, South Africa, Japan, and China are conducting a limited amount of research on fuel designs for gas-cooled test reactors and generation IV gas reactor concepts.

Categories of Fuels Research

The two primary areas of proposed advanced fuel R&D are (1) improved performance and advanced fuel design for existing light-water reactors (generation II and generation III) and (2) advanced fuel designs and related fuel cycle requirements for generation IV reactor designs.

The R&D program for existing light water reactors should involve government-industry collaboration and should follow two tracks. One track should focus on improving burnup limits considering evolutionary improvements to current fuel design, and the second track should focus on achieving maximum economical burnup limits considering new fuel options. In both cases, identification of plant operating limits and regimes and obtaining NRC regulatory approval of final designs must be an integral part of the R&D program. The program should include the following areas of R&D:

- Hot cell examination of current fuel designs to enable an understanding of life-limiting phenomena, and to provide a foundation for increasing the burnup capability of existing designs.

- In-core performance assessment so that operating characteristics of higher-burnup fuel can be identified considering steady-state conditions, transient conditions, and breached cladding conditions.
- Provision for obtaining criticality safety data and reactor physics data for benchmarking of codes and methods to address enrichments above 5% and development of the infrastructure to support licensing of fuel at the increased enrichment.
- Thermal-hydraulics, materials, and nuclear phenomena (including post-failure phenomena) experimentation to benchmark existing models and to support the development of new models for fuel performance and assessing operating margins.

Proceeding in parallel with the R&D program proposed above for existing reactors, the generation IV reactor advanced fuel cycle R&D program should include the following broad areas of R&D:

- Fuel systems for long-life cores (e.g., no refueling for 10+ years or cores that are designed for the duration of the plant life).
- High temperature fuel and materials performance.
- Passive fuel and core response (i.e., benign consequences of fuel failure or benign fuel response to off-normal events).
- Incorporation of advanced information technology and “smart” technology into fuel management and fuel cycle concepts.
- Utilization of Th/U-233 based fuel cycles.

In all of the generation IV reactor fuel cycle R&D considerations, both front-end fuel design requirements and back-end waste disposal characteristics should be explicitly assessed. For example, novel recycle/reuse technologies should be explored. Also, the research plan should include a specific strategy to merge the fuel cycle R&D with the generation IV reactor R&D program.

Funding

The advanced fuel/fuel cycle R&D program should be considered a 20-year program, because of the time period required to prove new fuel concepts. This program should produce qualified fuel products for existing light water reactors within 10 years or less and generation IV fuel products within 15 to 20 years. The second track of the R&D program for existing plants would extend over about a 10 to 15 year period. For current budget planning purposes, it is assumed that four fuel type/fuel cycle options for generation IV reactors and two fuel type options for existing LWRs would be studied over the first five years of the program. It is further assumed, for budget purposes, that after these first five years, full-scale R&D programs culminating in qualified fuel products would be pursued on two generation IV fuel type/fuel cycle options and existing LWR fuel options.

Within the bounds of a program design as outlined above, it is estimated that the budget required over the 20-year period would be about $750 million, including about $100 million for research reactor and other facility modification costs. The facility expenditures relate to having the TREAT facility available for testing higher burnup fuel for existing reactors and for potential generation IV fuels. For generation IV reactors, loops in TREAT for testing fuels to be used in potential gas or liquid metal reactor designs would need to be provided. Specifically, two loops of TREAT would be required, for a total of $20 million over the first five years. Also, the availability of a thermal spectrum environment, e.g., the advanced test reactor (ATR), is considered necessary for testing purposes. About $10 million would be needed for this use of the ATR. Similarly, *if* a fast spectrum reactor emerges from the screening phase, then a fast flux environment, for example, the fast flux test facility (FFTF), will be needed.

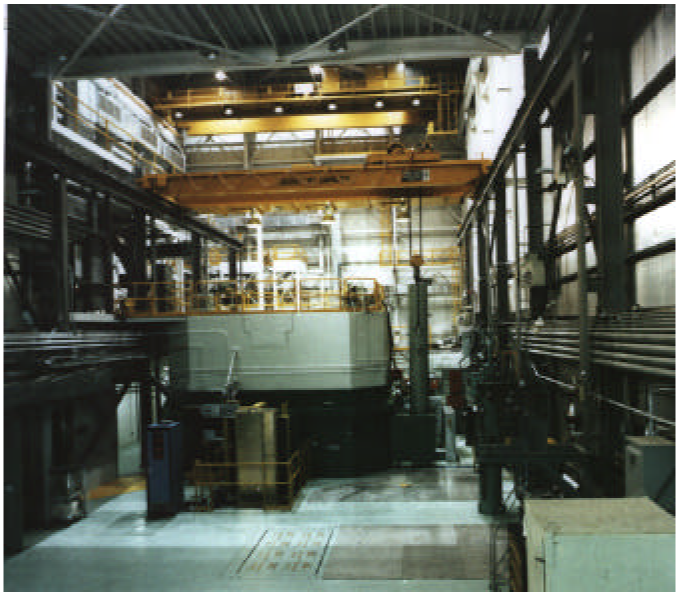


Figure 7. Transient Reactor Test Facility (TREAT) at Argonne National Laboratory (West)

Over the next five years, expenditures of about $40 million/year will be required, which includes about $12M for higher burnup fuels in existing reactors. As part of the industry-government collaboration on the existing reactors, about $6M in contributions from the private sector (possibly in-kind) would be provided to supplement the $12 M in the above budget.

1ST 5 Years	Fuels	$180M
	TREAT-loops	$ 20M
	ATR	$ 10M
	Sub-total	$210M
5 to 20 Years	Fuels	$460M
	FFTF-loop *if* fast spectrum cores are to be included.	$ 80M
	Sub-total	$540M
	Total	$750M

B. Plant Operations and Control, including Probabilistic Risk Assessment, Human Factors and Organizational Performance

Advances in information technology, sensors, instrumentation, controls, communications, simulation, and numerical models provide considerable potential for improving the safety, reliability, and economics of nuclear power plants (NPPs). Benefits are expected from design through construction, operation and decommissioning; gains would accrue to the current fleet of plants as well as to Generation III and IV. Detailed, timely, and accurate measurements of plant performance can improve safety and economics by allowing operations and maintenance to be fact-based and by eliminating unneeded margins. Thoroughly validated simulation codes and sophisticated databases would make it possible for the experience and wisdom learned across the industry and throughout a plant's life to be used in real time to support design, operations, maintenance, and decommissioning decisions. A systematic and sophisticated understanding of the role and behavior of plant personnel in normal and emergency situations could help guide nuclear power plant operations, including operator training. Improved control rooms would provide a more intuitive and natural human-machine interface with the potential for better and safer operations with fewer operators and maintenance personnel. In addition, research progress can have large beneficial effects on new plant construction by reducing commodities (e.g., cables) and installation effort.

Demonstrable, readily-assessed, fail-safe performance from these technologies could be achieved. The solid technical basis developed would allow updating the nuclear power plant regulatory framework and licensing criteria in the instrumentation and control (I&C) area. Furthermore, research conducted to apply these state-of-the-art technologies is likely to help attract bright young people to careers in nuclear energy.

Looking toward the future, continued rapid improvement in information technologies, computers, and instrumentation is anticipated. However, the very short inherent time scale of product development and obsolescence in digital-based technology and instrumentation (about 18 months) contrasts with the multi-decade lifetime and investment-recovery period characteristic of a nuclear plant. Meshing these time frames is a major challenge addressed by the suggested research.

Topics covered include research to develop, adapt, and/or validate the following:

- advanced instrumentation, sensors, and read-out capability**;**
- fully integrated controls, with advanced and effective human-machine interfaces;
- integrated, phenomenological, real-time, and/or virtual-reality computational models and simulation tools; and
- human-factors research.

Many billions of dollars per year are invested by industry and government in advancing computational and I&C technologies. These investments are producing ever-more capable, inexpensive, fast, and reliable computers, sensors, materials, simulation models, and ways to use them. Present DOE-sponsored R&D on nuclear power plant uses of these technologies is very modest ($2.8M in FY1999) and limited to a few NERI grants. This effort is focused on adapting to nuclear power plants the progress in the underlying I&C technologies and should be continued. In addition, the US Nuclear Regulatory Commission (NRC) has sponsored and should continue the $1.5M confirmatory R&D program associated with digital I&C licensing.

Advanced Instrumentation

Advanced instrumentation includes devices, sensors, and means to communicate with, calibrate, maintain, and replace them. The goal of research on advanced instrumentation is to adapt, develop, and/or validate for use in nuclear power plant systems made of high-accuracy, robust, inferential, radiation-hardened, micro-analytical, and/or ‘smart’ sensors and devices; robust communications; on-line signal validation and verification; and condition monitoring.

The research should address the following generic issues:

- The impact of these devices on nuclear safety, such as reliability, need for redundancy, testing and certification of smart devices and embedded software, and the effects of radiation;
- The identification of specific applications where these devices have the potential for a significant positive impact on current problems or could significantly improve plant operations;
- The development of standards and methods for nuclear certification of these types of components;
- How to verify and calibrate their signals *in situ;* and
- Use and qualification of commercial-off-the-shelf (COTS) equipment.

For example, research could make fail-safe and practical a robust, wireless communication system for the power-plant environment, with its characteristic ambient EMI/RFI. Advanced sensor R&D should focus, among other things, on material selection and device/structure integration to achieve high overall performance (accuracy, lifetime, fault-tolerant, self-healing, etc.) in a high-radiation environment. Additionally, R&D could resolve issues currently impeding the use of COTS equipment for safety and non-safety systems in nuclear plants. Studies could develop techniques for on-line signal verification and validation and establish the foundations for coupling signals into simulations that assist the operators in real time. Key challenges are to assure the consistency of multiple sources of related information, to identify faulty sensor information, to account for uncertainties and fluctuations in the signals, and to establish system and component status for use in the subsequent simulations. Other projects could develop and qualify ‘smart’ instrumentation and equipment that can measure and analyze one or more parameters in a nuclear power plant and take appropriate action. Since many advanced applications require large numbers of distributed sensors, research will also be needed to obtain acceptable costs in the specialized nuclear application.

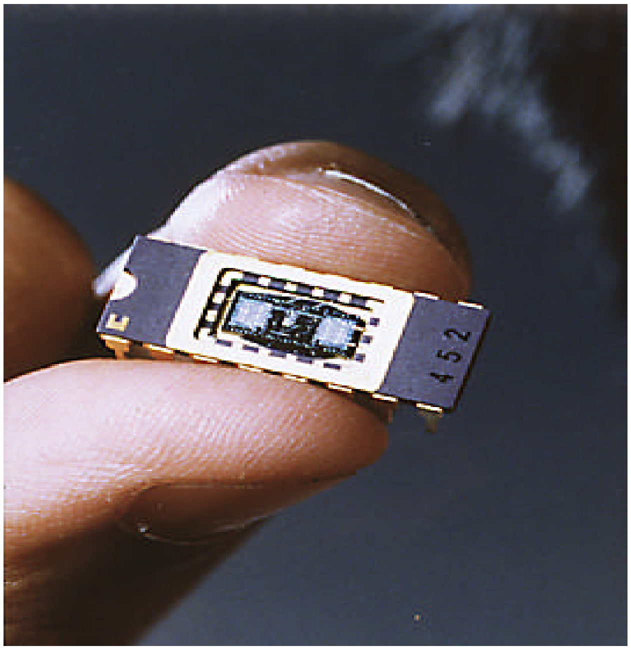


Figure 8. A researcher inspects a computer chip used in advanced control system circuits

Advanced Controls and Control Rooms

This topic addresses all aspects of plant control, operations, and maintenance. The research should build on general industrial progress in computing, networking, robotics, data analysis, and visualization to focus on specific nuclear power plant applications. One goal is to develop techniques that provide the optimum mix of human and automatic control to help ensure overall human-system efficiency, reliability, and safety. The research should lead to the availability of intelligent devices and sensors that can be installed throughout a nuclear power plant, make local control decisions, and be monitored from anywhere in the plant. Research should also improve the ability to measure and assure the reliability of digital and hybrid (combined digital and analog) control systems (including software, hardware, and their interaction) for nuclear power plant applications. The results will be essential for licensing such systems and for supporting revisions to the regulatory framework for addressing them without compromising safety.

A major challenge is to develop an interface through which plant personnel can obtain information effortlessly, when and where they need it, and in an immediately understandable form with no need to translate the presented data to obtain the information needed. The interface should be tolerant to personnel errors when they occur, i.e., minimize the chances that errors will occur and ensure error detection and recovery when they do occur. The research will enable the development of a fully integrated control room supporting plant monitoring, detection of disturbances, situation assessment, response planning, and response execution by a combination of crew members, intelligent agents, and automatic systems. Early steps include research on adaptive automation, advanced diagnostics and control algorithms, and advanced human-machine interfaces. The latter studies will focus on an integration of displays, procedures, and controls to provide a user interface that is capable of supporting all personnel operations and maintenance needs, including condition monitoring, accident assessment, and decision support. One goal would be to lay the foundations for expert teams to control and troubleshoot multiple plants from one location. Enhanced capability for remote monitoring also may advance non-proliferation objectives.

Figure 9. NUPLEX 80 Advanced Control Room design developed by ABB-Combustion Engineering

Research focused on advanced maintenance should enable risk-based maintenance planning, identify systems, structures, and components conducive to robotic maintenance, and develop robotic capabilities unique to nuclear-servicing requirements.

Modeling, Simulation, and High Performance Computing

DOE and its laboratories lead the world in high-performance computing and simulation. The recommended modeling and simulation research should exploit that capability.

The design and operation of nuclear power plants involves multiple interacting, dynamic, and time-dependent factors and phenomena. Current analysis and design codes have evolved since a time when computers and computational algorithms were orders of magnitude less powerful than they are today and our understanding of nuclear plant phenomena was less mature. It is now practical to develop codes that incorporate realistic phenomenology, integrate the relevant physics and engineering, couple between micro-scale and macro-scale processes, and/or that can simulate plant behavior in real time or faster. In addition, modeling technology should be advanced to allow the use of the same model from the initial plant concept, through design, construction, licensing, maintenance and operations, and decommissioning. The research in this area will develop and confirm high-fidelity, integrated, phenomenological, multi-physics, large-scale, computer models; real-time simulation tools; statistical models for component reliability; and virtual-reality platforms specific to nuclear power plant use.

Advanced simulations would enable improved real-time analysis to support operator decision making and maintenance planning. Models that accept plant condition information and run in real time (or faster) can guide operations and enhance safety under normal, off-normal, and accident conditions. Early models of this type are in use, but further advances and enhancements are needed. Simulations using these models will become valuable tools in design validation and personnel training. In addition, virtual-reality environments for design, construction, operations, and maintenance could allow users to move around in, interact with, and modify the nuclear power plant without requiring access to the real plant or building expensive mockups.

Human Factors and Organizational Performance Research

One roadblock to integrating personnel, software, and hardware systems is that our knowledge of the human processes involved in nuclear power plant monitoring and control is limited. Human factors research will form a technical basis to optimize the role of personnel in plant operations and the design of control rooms and human-machine interfaces. Research involving personnel representing a cross-section of the industry and related industries can elucidate such issues as: (1) the relationship between automation and operator vigilance, confidence, and performance; (2) the cognitive processes involved in situation assessment, diagnosis, and response planning; (3) the processes involved in team communication and coordination; (4) the application of new training modalities and approaches; and (5) the mechanisms of human error and their relationship to technology. The research should also lead to a more effective integration of personnel and automatic systems and to significant advances in the design of human-machine interfaces such as alarms, information systems, procedures, control, and support systems.

The safe and economic performance of a nuclear power plant is dependent upon the physical design of the system and the design of the organization that operates the system. Much research has been done to construct models of the physical system to allow for predictions of behavior. Advances in the capabilities of computers now make it feasible to develop models to simulate the influence of organizational structure and policies on system performance. The effects of organizational structure can be modeled in terms of how the processes of work creation, characterization, accomplishment, and approval are carried out in a given structure. The organizational structure influences how and what personnel are assigned to the work, and what resources are made available to conduct the work. Further, the quantity and quality of information available to different nodes of the structure affects performance. Finally, organizational policies, such as resource allocation policies and personnel training activities, are easily incorporated into simulation models. The research should lead to a new class of tools with which to study structure and policy in a non-intrusive, non-destructive manner.

The needed research should be conducted in cooperation with the nuclear utilities. The first phase of the research would be to create representations of the relevant process, i.e., work flow, resource allocation, information flow, and decision processes. The second phase would integrate these representations into a system dynamics model. The third phase would analyze a variety of structures to develop a deep understanding of how structure influences performance in a quantitative and reproducible manner.

Probabilistic Risk Assessment (PRA) Research

The objective of PRA (and its major strength) is to model the plant as an integrated system (a "socio-technical" system, in recent terminology). Current activities by both the industry and the NRC provide strong evidence that future decisions regarding plant performance and safety, as well as design choices for advanced reactor concepts, will be risk-informed, i.e., results and insights from PRAs will be a major input to the decision-making processes. There are both cultural and technical obstacles to the increased use of PRA. Major obstacles are the need for additional data and improved models. In addition, culturally, some people are not comfortable making decisions using this paradigm.

This requires research in the following areas:

(1) All modes of operation must be included in the PRA. Improvements in the models for assessing the risks from low-power and shutdown (LPSD) operations should be developed, taking into account the inherent time dependent nature of the problem as well as the numerous operator actions that take place, especially during transitions between operating states.

(2) Human performance is of major importance, especially during LPSD operations. The current paradigm is that operators will do the best they can given the context within which they function. This context is shaped by plant conditions (e.g., the discrete behavior of digital I&C systems may create unfamiliar conditions), psychological factors, and the culture at the plant. The last is the direct result of management actions and directives and years of operating practices. The research proposed under human factors in the I&C section of this plan addresses part of the context. Similarly, the human factors section deals with the resulting operator response. The results of these research efforts will satisfy part of the input required for PRA modeling. However, for PRA applications further research is needed to (a) integrate this information with accident sequence models sufficient to provide appropriate human performance models for risk applications; (b) model operator actions that create an abnormal situation during normal plant operations; and (c) formulate approaches to reflect the impact of plant culture on human performance.

(3) The decision-making process must be structured to allow for the utilization of PRA results and insights. As movement continues to more system-based analyses, the need to better formalize these processes will become greater. Research should be conducted on the decision making process for design tradeoffs, plant performance optimization, and safety-related decision-making. The extensive body of knowledge in the literature on decision making and optimization should be assessed as part of this research.

The emphasis in the preceding discussion has been on PRA. In addition, PRA-like models may be useful to optimize power production and therefore improve plant economic performance. Research should explore and develop such capacity.

Funding

In the near term, to accomplish the programs described in this section, DOE-NE should invest $18-20 million per year in the sensor, instrumentation, controls, simulations, modeling, human-factors, PRA, and organizational performance research summarized in this section, about two-thirds through NERI (or similar merit-based, competitive process) and one-third through NEPO or some other mechanism that selects quality proposals and requires at least 50-50 matching by industry. Some of the cost-shared research should address issues associated with licensing technologies for use in nuclear power plants. By FY 2005 the annual funding level should reach

$30 million, and DOE should consider making these technologies the focus for a specific program.

DOE should establish a facility (at one location or multiple linked sites) to support the research, development, and testing of advanced I&C, modeling, simulation, and control-room components and concepts. This facility should include virtual reality modeling and simulation capability. The first step, to specify the features for the facility and to estimate its cost, should be completed in FY2001, and the facility should be available before 2005. The facility should be able to be built within the funding recommended above.

In addition, DOE-NE should take responsibility for ensuring that Federal, industrial and international R&D efforts on nuclear power plant-related I&C, modeling, simulation, and human-factors are well coordinated. DOE should include in its selection of research projects tackling Generation III and IV issues a criterion that favors proposals that include at least 10% of the effort aimed at the related or underlying I&C, simulation, and/or human-factors issues. DOE should fund development of software, facilities, and knowledge available to and shared by all stakeholders, rather than held on a proprietary basis. University reactors should be considered, where appropriate, as possible test beds for advanced I&C devices and concepts.

C. Reactor Technology and Economics

The goal of this research and development program is to develop advanced nuclear reactor technologies that will allow the deployment of highly safe and economical new nuclear power plants. These would be a competitive electricity production alternative in the United States and foreign markets, while being responsive to environmental, waste management, and proliferation concerns. Pursuing this research is a policy decision, which NERAC strongly recommends.

The Department of Energy is engaged in a wide ranging discussion about the requirements and development needs for the next generation of nuclear power systems, the so-called Generation IV. The second generation of nuclear power systems, the class of operating PWR, BWR, CANDU, and VVER plants, is deployed around the world. The third generation of nuclear power systems, represented by the evolutionary Advanced BWR, System 80+, AP600, and EPR designs, is finding markets in Asia. Generation III also has the potential for expanding nuclear power capacity in Europe and the United States, but presently it is not economically competitive in those markets. In broad terms, the consensus is that Generation III and Generation IV systems must be cheaper to build and operate so they can compete in a deregulated electricity market. They should be safer in design and operation, support improved waste management, especially of spent fuel, and disadvantage the fuel cycle from diversion for weapons use and therefore be more proliferation resistant. These are demanding criteria.

The overall objective of this research and development program is to provide the technical basis for competitive Generation III and Generation IV nuclear energy systems in deregulated electricity generation markets. For Generations III and IV, the specific objective is 3¢/KWh total busbar cost, down from the present 4.1¢/KWh. This is competitive with the present market price for natural-gas-fired combined cycle electricity of 2.5-3.3¢/KWh total busbar cost. This objective assumes that fossil plant competition will not be hindered by internalization of the cost of greenhouse gas emissions (for example, with a carbon tax) and that fossil fuel supply will remain stable and the price will not increase above average inflation levels in the long term.

Research Strategy

The plan's strategic basis is that there are R&D results generic to both Generation III and IV that should be available before 2010. Further, there are other results, specific to preparation for the demonstration of Generation IV systems, that will not reach fruition until after 2015. The overall results, therefore, will contribute to the economic competitiveness of Generation III systems deployed in the near term and the introduction of Generation IV systems in the longer term.

A research strategy is recommended having both near-term results (for deployment in the next 5-15 years) and long-term results (for deployment in the next 15 years and longer). The first area of research would focus on improvements to existing Generation III designs. The second area of research would comprise the advanced Generation IV reactor research, and look into new uses for nuclear energy, such as supporting a hydrogen economy. The main research areas differ by reactor generation.

For Generation I and those Generation II plants shut down in the 1990's, decontamination and decommissioning (D&D) is the central R&D issue today. For the majority of Generation II plants, operations and maintenance (O&M) costs, technical support for a risk-informed regulatory process, and aging mitigation are the central R&D issues. Lessons learned and technologies developed will improve safety and performance and benefit future generation plants. Improvements in the regulatory process can remove unnecessary economic burdens on current nuclear plant operations. For Generation III plants, improved construction (capital cost) economics and O&M costs are the central R&D goals, working from the existing base of advanced LWRs (ABWR, System 80+, and the AP-600). Opportunities on the technological forefront include modular construction, application of virtual construction and project management techniques, and risk-informed methodology for use in safety regulation.

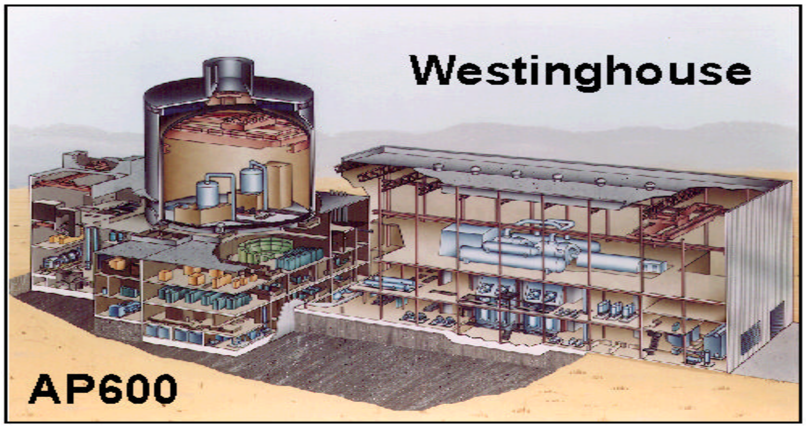


Figure 10. Westinghouse AP600 advanced light water reactor design (Generation III)

For Generation IV designs, the central issue is "What technology is most compatible with a global market economy?" The expectation is that with a substantial technology step from Generation III to IV, many process improvements will flow from III to IV, but not all improvements will be relevant. Generation IV nuclear plants will face new challenges in reduction of capital cost and of investment risk from waste management, safety, non-proliferation issues, and regulatory approach.

The recommended R&D program includes advances in system design and methodologies and technologies associated with the design, fabrication, manufacturing and construction, and operations and maintenance of nuclear plants to reduce costs, while conforming to safety, environmental, and non-proliferation requirements. In the following, research topics are organized in four categories:

- System design and new concepts,
- Capital costs and construction time,
- Efficiency/output, and
- Generating costs (including capacity factor and O&M costs).

Successful R&D on improved system designs and new concepts can enhance the economic and safety performance of nuclear plants, extend their contribution to energy needs beyond the electrical sector, and greatly increase their fuel utilization and reduce wastes. The high capital cost of plant structures and equipment and long construction time (experienced with present nuclear plants) puts a high priority on modularization and the application of advanced technology to virtual construction planning, procurement process control, and configuration management. R&D on higher temperature performance, more efficient turbines, the addition of topping cycles, and alternative cooling cycles can improve the efficiency of nuclear plants, and thus increase their economic competitiveness. Lower generating costs through higher capacity factors and reduced O&M costs can be achieved by R&D on higher burnup fuel, advanced I&C, human performance/human factors, and advanced aging management and maintenance technologies.

The Research Agenda

The reactor technology research program is organized into major phases: (1) starting with a focused review of technologies to reduce the capital costs of Generation III plants, and an exploration of a variety of Generation IV reactor concepts; (2) conduct of key technology research, progressing to a selection of one or more leading concepts; and (3) a culminating major focused construction program requiring testing and prototype construction and operation for Generation IV to demonstrate market readiness.

The initial phase of the program (2002-6) grows out of NERI and prior design activities to explore a broad portfolio of system design candidates for longer-term, revolutionary Generation IV plants, and options for major capital cost reduction for deployment of Generation III plants. The system design efforts will serve to identify key technology issues for focused research. In addition, the research program will address key technology issues for Generation III and IV plants that respond to capital and generation cost issues, including advanced fabrication and construction technologies and modularization approaches.

Assuming continued US government support, the second phase of the program (2007-10) would continue the focused research program, which, if successful at responding to the key technology challenges, allows for a down selection to one or more promising system Generation IV concepts for further development, and provides final plans, but not government funding, for construction of one or more Generation III plants in the United States. In addition, the technical basis for the licensing methodology for advanced Generation IV systems will be developed.

In phase three, beyond 2010 and applicable to Generation IV, major components and systems will be designed, tested and demonstrated, the formal design will be completed, and the design will be submitted for licensing approval. A final phase (beyond 2010) will be needed as phase three of the program is completed. *Given sufficient private and public funding commitment*, a prototype plant would be constructed to prepare the Generation IV plant design for broad market availability.

System Design and New Concepts

If nuclear power is to continue as a major source of electricity generation, new approaches need to be taken to develop the advanced reactor technology that will respond to the major market and public acceptance drivers in the 21st century. These drivers include substantially lower costs to improve the economic competitiveness of nuclear power in the global energy market, continued improvements in safety, better managed and reduced quantities of radioactive wastes, and improved proliferation resistant characteristics for worldwide deployment. Major effort is needed on Generation III designs and supporting construction technologies to achieve lower capital costs with the same or improved safety characteristics.

For Generation IV designs, innovative approaches can be developed from a broad exploration of advanced reactor system conceptual designs that identify the physics, thermal, mechanical, safety, economic, and other performance characteristics of the proposed Generation IV concepts. Design criteria and performance requirements will be developed for Generation IV systems with international community involvement. For those concepts that appear attractive from this preliminary examination, the key technological issues will be identified for further research. Several generic technology issues, including the behavior and performance of advanced fuels, coolants, and high temperature materials, and smart equipment, including digital instrumentation and control approaches, will emerge as enabling technologies. For specific concepts, key issues may be identified in advanced energy conversion technologies, proliferation resistant technologies, advanced waste management technologies, and others. Some concepts may enable broader missions including hydrogen generation or advanced process heat applications.

It is envisioned that the advanced reactor concepts will fall primarily into one of three broad categories: major advances in advanced light water cooled reactors, high temperature gas-cooled reactors, and liquid metal or other high-temperature-fluid cooled reactors.

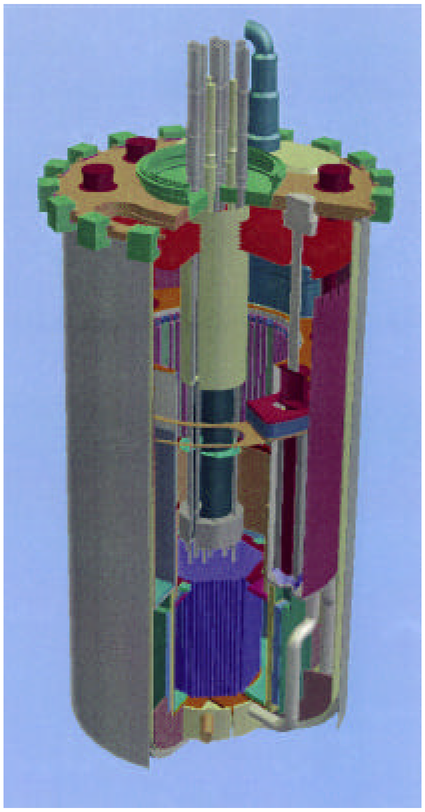


Figure 11. Concept drawing of General Electric's Super Prism advanced liquid metal reactor design

Major improvements in light water cooled reactor technology initially will focus on the needs of Generation III: capital and construction cost reductions, primarily through advanced modular construction techniques; improved design for cost effective maintenance; advanced information system management systems; and up-dated, risk informed regulatory methodology. Longer term advancements to light water technology are envisioned in areas such as high-efficiency, lower-cost superheated steam or super-critical water cooled systems; longer life, more resource efficient, more proliferation resistant fuels; spectral shift and "fast" spectrum cores; fuel reuse technology; advanced high temperature and long life materials; unique deployment options such as small manufactured reactor systems; natural or passive safety systems; and advanced, low-cost containment and other major systems.

High-temperature, gas-cooled reactor systems offer the potential for high thermal efficiency, fundamental improvements in system capital cost compared with existing light water reactors (perhaps through factory-built modularization), and different approaches to safety performance. Major research is needed in fuel performance, including demonstration of the safety performance of the fuel under accident conditions; engineering development and demonstration of direct cycle, high temperature turbomachinery and associated components, such as magnetic bearings, high temperature/high voltage connectors and insulators; and multiunit digital control systems. A major effort also will be needed to develop the safety case for these designs, especially for those that rely solely on the fuel to provide containment.

There is a broad category of advanced reactor system concepts that utilize liquid metal (Na, Pb, Pb-Bi) or other high-temperature fluid (molten salt) coolants to achieve high efficiency, improve fuel utilization and actinide burning, waste minimization, improved proliferation resistance, and passive safety. All of these concepts present high temperature material compatibility issues, require advanced fuels, involve reactivity control challenges, and present opportunities for very advanced energy conversion technology applications. The fuel utilization potential of these designs would become important were uranium supplies not to keep up with demand. Finally, there will be basic nuclear data and reactor physics integral data needs because of the fast spectrum and new materials employed in these systems.

For all of the design concepts, there are cross cutting research topics related to the development and application of advanced simulation-based design methods such as are applied in the aerospace and other industries, application of advanced instrumentation and automated control systems to improve the safety and efficiency of operations, transparent and effective technologies to improve the proliferation resistance of the reactor and fuel cycle, and an integrated approach to waste minimization and spent fuel management. Finally, the capital cost reduction, efficiency, and generation cost reduction R&D discussed in the following section are expected to be largely applicable to both Generation III and IV systems.

Capital Cost and Construction Time

The largest contributor to the busbar cost of electricity produced by a nuclear power plant is the specific capital cost of the plant ($/KWe). The construction time is also important because plant capital is invested over this period of time without any revenue from the sale of electricity. Significant reductions in both specific capital cost and construction time from those typical for Generation II plants are needed to achieve cost competitiveness in today’s market environment. Generation III plants, developed under the joint Government-industry sponsored ALWR program, resulted in significant reductions through plant simplification, equipment reductions, commodity reductions and the adoption of modular construction approaches. Further cost reductions are necessary for Generations III and IV to be cost competitive in tomorrow’s market.

Following are R&D topics that provide high payoff value for achieving competitive costs for Generation III and IV plants.

- Optimization of Generation III and IV system designs with a specific focus on dramatic reductions in capital costs.
- Adaptation/Demonstration of virtual construction, automated processes, and management techniques. Techniques have been developed in other industries to optimize and manage highly complex construction projects to minimize construction time and risks.
- Alternative construction materials.
- Optimization of module size and configuration.
- Modularization: manufacturing, construction technology, field assembly, and certification.
- Welding technologies. Development of technologies to further reduce the time and cost of welding piping systems, containment shells and wall lining will benefit both Generation III and IV plants.

Figure 12. Advanced concepts in robotics could improve nuclear power plant construction and maintenance efficiency, with a potential for improved economics.

In addition, developing of a more risk-based approach to establish new bases for designing and licensing future plant designs would provide designers with substantially increased flexibility to reduce costs while maintaining high safety standards.

High economic payoff may also be possible with older Generation II plants through development of means to repower them when their major components reach end-of-life. Major component replacement (e.g., reactor vessel, reactor internals) and other upgrades could preserve the value of a sizable asset with modest additional investment.

R&D topics that provide a more modest payoff for achieving competitive costs for Generation III and IV plants include:

- Analysis and optimization of structural margins and/or use of alternative methods (e.g., to reduce or replace reinforcing structure).
- Transportable deployment options.
- Containment liner technology (to reduce cost of steel lined concrete, e.g., with advanced concrete coatings).

Efficiency/Output ($/KW or KWh)

Like direct capital costs, plant efficiency has a strong effect on busbar cost for electricity produced by nuclear power plants. These topics are included here for completeness. However, since many are directly industry improvements, major cost sharing with industry should be required for government funding in these areas.

The most important high-payoff R&D opportunity for achieving high efficiency is the development of nuclear systems and materials focused on operation at higher temperatures. Both Generations III and IV will benefit from this development, with Generation IV being totally dependent on success in this area. Materials R&D items are identified in Chapter II.

Medium payoff R&D items for improving plant efficiency or output include:

- Topping cycles to be added to nuclear steam cycle (e.g., combustion superheating). This R&D is applicable to Generation III plants and potentially to some Generation IV plants.
- Instrumentation and control to optimize power. Advanced sensors to accurately measure key plant parameters will be applied together with control and protection logic, to increase power output. This R&D is applicable to both Generation III and IV plants.
- Secondary working fluid technology. Alternate working fluids (e.g., organic) in the secondary energy conversion system can lead to increased efficiency in some Generation IV concepts.
- High efficiency turbines. The efficiency of both Generation III and IV plants can be increased through development of high efficiency turbines. Advanced turbines can provide modest (e.g., 10%) efficiency increases without increased system temperatures.
- Bottoming cycles. Employing means to use the waste heat from nuclear power plants can add value if they can be employed without large capital additions. Examples include desalination and process heat.
- Operating margin improvements. Advanced analytical methods that result in increased accuracy in predicting plant performance can provide increased operating efficiency for Generation II, III, and IV plants.
- Power upgrade to Generation II Plants. Improved I&C and/or improved fuel designs can provide increased power output when used in currently operating plants. While some of the required R&D is being conducted by equipment suppliers, other items are identified elsewhere in this report.

Generating Costs (Capacity Factor and Operating and Maintenance Costs)

The busbar cost of electricity also depends on the KWh that can be produced in an operating cycle and the cost of operating and maintaining (O&M) the plant over the cycle. Minimum cost results from maximizing the plant capacity factor and minimizing O&M costs.

Following are R&D topics that provide high payoff in this area.

- High burnup fuel. The use of high burnup fuel can result in reduced outage time and increased capacity for Generation II, III, and IV plants. Fully achieving these benefits for Generation II plants will require license renewal.

- Advanced sensors, controls, diagnostics, simulation technologies. Capacity increases through reduction in planned and unplanned outage time can be achieved in Generation II, III, and IV plants by employing such technologies. Enhanced outage planning and online maintenance are facilitated by use of such technologies. The results from the R&D proposed in Section II-B will contribute to effecting these improvements. To obtain the reduced outage time benefits of high burn-up fuel, further advances in maintenance technology will be needed to permit continuous operation for long periods of time (> 2 years).

- Management of plant aging**.** Development of techniques to manage the aging of plant systems, components, and structures from the design phase and through to the operations phase can provide increased plant life and lifetime capacity. Generation II plants are currently involved with such activities. Generation III and IV plants can benefit by considering the lessons learned in design activities and plant operating guidelines, for example, as detailed in the Utility Requirements Document developed in the ALWR program and approved by the NRC.

- Advanced maintenance technologies**.** Reduction in maintenance time and resources will result with the maximum use of standardized equipment, simplifications that lead to reduced requirements for equipment maintenance or quantities of equipment, the application of human factors to minimize maintenance personnel error, and the use of “smart” equipment. Generation II, III, and IV plants will benefit from such technologies.

- Improved major component reliability**.** Steam generators are used in some high temperature Generation IV concepts. High reliability of these components will be required to minimize costs and to achieve long periods of operation between extended refuelings. Development of highly reliable steam generators is required.

One R&D topic providing medium value in this area involves decommissioning technology. Most Generation I and a few Generation II plants have been or soon will be decommissioned. Valuable lessons learned need to be captured and transferred to Generation II nuclear power plant owners and Generation III and IV nuclear power plant developers to provide them the opportunity to use the lessons in planning and designing to minimize decommissioning costs.

Several R&D topics of somewhat lower payoff were identified in this area. They include the following:

- Improved in-service inspection (ISI) technologies. Generation II, III, and IV nuclear power plant economics can all benefit from such technologies (e.g., NDE, NDA, robotics) through reduction in outage time.

- Improved decontamination technologies. Generation II, III, and IV nuclear power plant economics can all benefit from technologies that reduce the cost, time required, and personnel exposure associated with surface decontamination during plant outages.

- Coolant chemistry control. Strict control of coolant chemistry in Generation II and III plants is essential to maximizing component reliability and life. Improved technologies will increase total plant capacity and minimize outage time.

Funding

The funding profile for the first phase of the "R&D Plan to Achieve Economically Competitive Nuclear Power", is listed below by the main topic area:[4]

R&D Topic Area	FY 02	FY03	FY 04	FY05
System Design and New Concepts	$20M	$25M	$30M	$40M
Total Capital & Construction Time	$5M	$5M	$5M	$10M
Efficiency/Output	$5M	$5M	$5M	$5M
Generating Cost (Capacity Factor, O&M)	$5M	$5M	$5M	$5M
Total	$35M	$40M	$45M	$60M

The total five year cost for phase I (2002-2006) is $250M. The funding profile for the phase II programs described would be in the range of $100M annually (2007-2010). Funding for phase III, which includes major component testing, would require substantially larger funding, the magnitude of which depends on several factors including the availability of appropriate test facilities. This may be in the range of $150M annually.

Generation III and Generation IV reactors are envisioned as products for the 21st century world market. As such, the development and testing of Generation IV technology would benefit greatly from international participation. The preceding funding profile assumes considerable international leveraged-funding, at least equal to the US effort.

Facility Needs

There are several classes of facilities required to design, develop, test, and demonstrate advanced reactor technology. To a large degree, many of these facilities exist in various states of usability in the United States and around the world. The Nuclear Energy Research Advisory Committee (NERAC) subcommittee on Infrastructure is evaluating the existing US facilities at DOE national laboratories, and will have to assess equally the university, industry, and international capabilities in order to develop a comprehensive facilities infrastructure plan (roadmap).

---

[4] Details are available for each element.

The reactor technology research program will require the following types of facilities:

- Hot cells, test reactors, and fuel fabrication laboratories for advanced fuel development and testing.
- Thermal-fluid systems test loops for water (including superheated steam), gas, liquid metal (and other high temperature fluids such as molten salts) for both separate-effects and integral-systems testing.
- Engineering test facilities for high-temperature, high-efficiency energy conversion components and systems (e.g., turbomachinery and advanced steam generators).
- Non-aqueous fuel “recycle” process development facilities.
- Advanced simulation laboratory(s) for development and testing of digital I&C systems such as multiunit control systems.
- High-temperature materials fabrication and testing laboratories.
- Hydrogen process research laboratory.
- Nuclear cross section measurement facility(s).
- Critical experiment facility(s) for both physics measurements and nuclear criticality safety measurements.
- Full scale Generation IV reactor prototype for testing/licensing/demonstration.

The DOE-NE facilities infrastructure plan will need to consider a wide variety of technical, cost, international, and political issues, as well as systematic preservation of critical US core competencies, in placing facilities and missions at government and industrial research laboratories, universities, and international laboratories to optimally support the development and demonstration of advanced reactor systems.

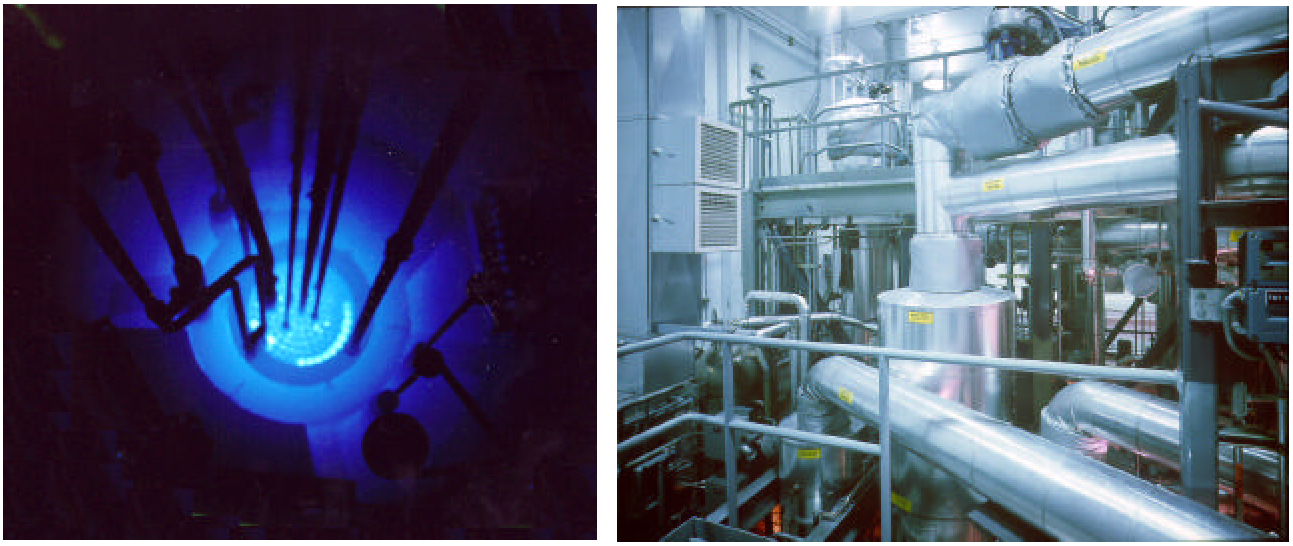


Figure 13. Some universities maintain nuclear engineering research facilities. Shown are the TRIGA research reactor and the APEX scaled ALWR test facility at Oregon State University.

IV. ISOTOPES AND RADIATION SOURCES

Radioactive and stable isotopes and radiation sources are widely and increasingly used in medicine, research and industry. DOE-NE has a major role in isotope research and production, which is the subject of this section.

Overall, the isotopes managed by DOE, which as used in this document include radiation sources, fall into three categories:

- *Programmatic*: Isotopes that have identified uses by specific programs. This category is primarily composed of isotopes for the national security missions of DOE-DP and DOE-MD, e.g., highly enriched uranium and weapons-grade plutonium.
- *National Resource*: Quantities of stable and radioactive isotopes that are
  - Identified for use by so many programs that there is no single program obviously responsible for the isotope (e.g., Cf-252 and Pu-238), or
  - Surplus to presently identified program needs but potentially valuable to future programs, and which would be very difficult and costly to recreate (e.g., heavy actinide isotopes such as Pu-244 and U-233).
- *Waste*: Materials that have no present programmatic use and where the potential for any future use is so low that it is not cost-effective to separate and maintain them as a national resource. This category includes many nuclear materials that are mixed with hazardous chemicals or present in trace amounts.

The scope of this section is national resource isotopes, with the exception of Pu-238, which is discussed in conjunction with space power systems.

Isotopes, both radioactive and stable, are essential for several critical areas of national importance to health, safety, and industrial development and international competitiveness. These include the following:

- Medical applications: Diagnosis and therapy of a range of diseases relies upon isotopes, both applied directly for treatment and diagnosis. Overall, the biomedical community uses more than 200 radioactive and stable isotopes for research, drug development, and for diagnosis and treatment of diseases. Continuing advancements in medicine depend upon a reliable supply of useful isotopes for known applications. Many next-generation medical diagnostic and therapeutic approaches depend upon the availability of small amounts of many isotopes for research purposes and development of new or improved production methods for isotopes for which the research is successful.
- Industrial usage: There are numerous vital applications of isotopes, including industrial radiography, measurements of chemical, elemental, or physical parameters of samples and bulk materials, thickness gauging, runway safety lights, smoke detectors, initiating chemical reactions, and sterilization.
- Research: Research relating to medical, industrial, agriculture, and the natural and physical sciences use isotopes as tracers or as external radiation sources. Examples include

biomedical research, materials testing, the environmental transportation of isotopes, and others.
- Federal programs: Isotopes are needed to support the work of government agencies, primarily related to national security applications.

The use of isotopes in the above applications, estimated to be growing at 7-15% per year, faces major challenges: institutional complexity; difficulty in measuring economics and benefits; lack of central leadership; public perception of risks, benefits, and reliability; maintenance of technical expertise; and deteriorating infrastructures.

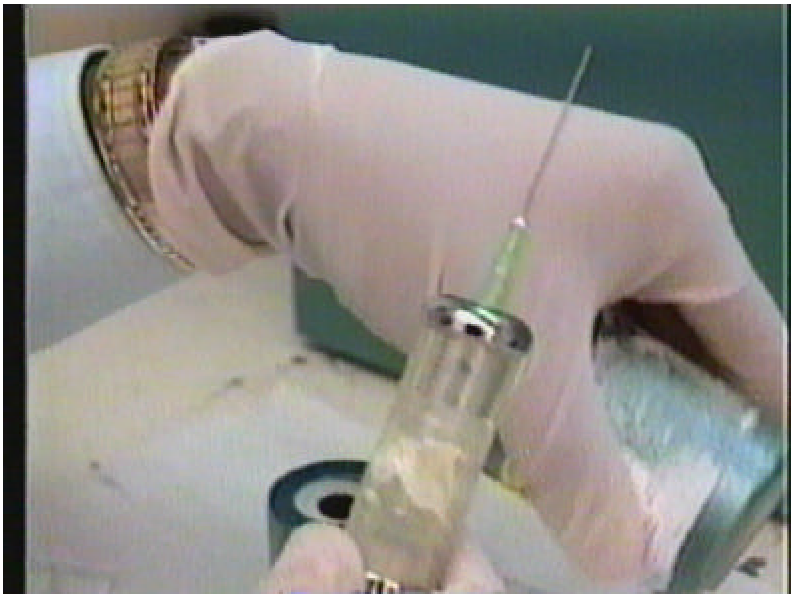


Figure 14. Injecting medical isotope tracers for diagnostic screening

Activities relevant to determining DOE-NE's isotope mission are discussed in two categories: strategic and technical.

Strategic activities. There are three activities important to strategic planning for DOE-NE's isotope programs:

- Integrated Nuclear Materials Management Plan: This plan, prepared at the direction of Congress, presents an integrated view and future of how DOE will manage its nuclear materials, and designated DOE-NE as the program office responsible for managing national resource materials.

- Report of the NERAC Isotope Research and Production Planning Subcommittee: This report, which is being considered in parallel with this plan, surveyed the demand for isotopes and DOE's ability to meet the demand, and formulated recommendations in this regard. Key recommendations are that (1) DOE is not meeting the demand for research isotopes and needs to refocus its efforts, (2) the production system must be viewed as an integrated set of federal, university and commercial supplies, and (3) a dedicated research isotope production capability (including both a cyclotron and small reactor) is needed in the long term.

- Report of the NERAC Infrastructure Subcommittee: This report surveyed and evaluated the need for and availability of key physical infrastructure that is, among other things, a vital resource for isotope production. Key conclusions are the following:

  - There are insufficient resources and priority for research isotope production. At current funding levels, the federal isotope production sites have difficulty maintaining their infrastructure and giving support to the production of research isotopes.
  - The existing isotope production program relies on multiprogrammatic facilities where isotope production aspects are not the primary mission. The only complete solution to the problems caused by this parasitic radioisotope production is to take steps to provide dedicated, yet modest, facilities for radioisotope production in the future.
  - DOE sites, as an aggregate, have more than adequate processing capability today, especially hot cells and processing equipment, relative to their system-wide use.
  - Several research isotope supplies outside the national laboratory system offer significant, if not superior, production capability.
  - No overall strategy exists regarding the designation of preferred reactor and accelerator sites.
  - DOE policies for its commercial and research isotope supplies are appropriate.
  - The supply of research isotopes involves many subjective decisions and tradeoffs.
  - DOE is sometimes reluctant to cease its production of commercial isotopes that the market could reliably furnish. This is because DOE's production of commercial isotopes brings significant revenues to the production sites, which helps to maintain their infrastructure.
  - Previous recommendations to support graduate and postgraduate training have not been addressed, and now a desperate situation exists in the disciplines of nuclear and radiochemistry.
  - The FFTF will not be a viable source of research radioisotopes. In particular, the operations at the Missouri University Research Reactor and the High Flux Isotope Reactor are better suited to meeting the demands of users who need small quantities of research isotopes at irregular intervals.

  These must be tempered by the fact that the study has not yet been extended to include university and international infrastructure.

Technical activities. There are many ongoing activities related to isotope research and production. These are summarized as follows:

- Research on isotope applications: DOE-NE, DOE-SC, and the National Institutes of Health (NIH) are estimated to spend, respectively, on the order of $2M, $20M, and $200M annually for research on isotope and radiation source applications, primarily related to medical diagnostics and treatments. There also are studies being supported by the Department of Defense and being considered by NERI on the use of x-rays to cause stable isomeric states of certain isotopes to cause accelerated release of gamma rays. There is essentially no federal R&D investment in non-medical uses of isotopes and radiation sources.

- Isotope production: DOE-NE invests about $20M/yr to produce and inventory isotopes. Most of this produces bulk quantities of isotopes for established applications for which there is an insufficient or unreliable commercial supply.. It is estimated that the investment in producing research isotopes is only about $2M/yr.

Research Strategies

Presently, DOE's isotope program and, thus, efforts within the United States to beneficially use isotopes are limited by budget and other institutional constraints. In the future, DOE-NE's isotope mission should be broadened to be the following: Improving the quality of life and economic competitiveness of the United States through isotopes and radiation sources for research, medicine and industry.

DOE-NE's roles will include (1) production and inventory of isotopes for research, medicine and industry, (2) research and development on isotopes, (3) fostering the application of isotopes, and (4) management of national resource isotopes.

DOE should aspire to the long-term vision of being the leader but not manager or controller of an enduring, cost-effective isotope program with visible public benefits. Achieving this will require that the DOE stimulate and expand the research into the beneficial uses of isotopes, and foster the development and use of these technologies. At the same time, the DOE must take steps to improve and assure the supply and inventory of isotopes. Needed research into isotopes divides broadly into two major strategic arenas involving research and production plus other strategies related to infrastructure, education, and waste management as described later in this plan.

Isotope Research

The following strategies are recommended to support isotope research:

(1) Focus on isotope applications not being supported by other Federal programs. It is recognized that there is a large amount of medical research (both basic and applied) on diagnostic and therapy modalities which are typically funded by NIH and/or DOE-SC. That research is primarily focused on the effective detection and diagnosis of a disease, or the basic physiological and/or therapeutic response of a disease to radiation. It is much less focused on the development of innovative radiation sources or radioisotope production and delivery systems. The DOE needs to balance this medical emphasis with research into a number of areas which can complement the ongoing medical research, stimulate new and beneficial applications for industry, and enhance environmental, life sciences, agricultural and food safety research.

Specific elements of this strategy are the following:

- Establish formal coordination mechanisms with NIH and DOE-SC to ensure that isotope research programs are complementary.
- Innovative radioisotope delivery systems and radiation sources based on novel isotopes, sources, equipment or methods that will result in new and unique applications not generally covered by the established sources of medical research funding.
- Research on uses of isotopes outside of medical applications.

(2) Invest in R&D to improve isotope production, processing, and utilization. This includes improving both the technical aspects of isotope production (e.g., target design and fabrication, processing, transportation) as well as the systems that enable isotope generation and utilization (e.g., safety systems). Important elements of this strategy are the following:

- Technology for stable isotope separation that affords low-cost production with maximum flexibility in the choice of element.
- Investigation of beneficial uses for radioactive waste constituents, and technologies that can recover useful products from wastes.
- Research that improves the radiation safety of radioisotope production in nuclear reactor and radiation beam facilities, such as automated radiochemistry processes, novel facility design and shielding, detection systems for monitoring inventory, production and waste streams.
- Research on improved sealed source types and packaging technology and approaches to decrease the production of waste for these sources.
- Encourage and fund collaborative efforts between industry, universities and/or national laboratories that achieve improvements in commercial technology. Create and encourage User Groups for isotopes and sponsor topical workshops and seminars.

Production and Inventory

While not research *per se*, producing the proper array of isotopes and maintaining adequate inventories is an integral part of isotope research to the point that production and inventory must be considered as part of the research strategy.

(3) DOE-NE should be responsible for managing US national resource materials. These materials, some of which are difficult or impossible to replicate but which have no current use, are vital to the future of beneficially using isotopes. Key elements of this strategy arethe following:

- Leading a multiprogram effort to establish and implement a process and associated criteria for deciding which nuclear materials should be retained as national resources.
- Establishing and implementing a national resource management plan to integrate management of national resource materials and to provide a basis for transferring existing funding or requesting new funding as necessary.
- Participating with other elements of DOE to establish a broader nuclear materials program that integrates program, national resource, and waste isotope management.
- Establishing an office constituting a single point of contact to provide leadership and coordination of national resource isotope research, production and inventory and also

recognize the different requirements of this mission as compared to bulk isotope production and sales.

(4) DOE-NE should lead a multiprogram effort to assess responsibilities for the current isotope and radiation source infrastructure with the goal of streamlining responsibilities. Currently isotope production depends on facilities within the purview of multiple DOE programs (NE, SC, DP) and some facilities are funded by one program but managed by another. In addition, considerable relevant university, commercial, and international infrastructure must be considered. The objective of this strategy is to better align responsibilities while maintaining necessary relationships to multiple use facilities.

5) Invest and organize to meet the needs of isotope researchers. The current supply is not able to meet the needs of the research community for promising, yet rare or difficult to produce radioisotopes, such as iodine-124, bismuth-212 and -213, and copper-67. In addition, long-term supplies of stable isotopes are not assured since the DOE has halted production in the wake of low-cost Russian supplies. The following actions are recommended:

- Produce isotopes needed for vital medical and industrial research on a long-term basis and without assurance of their ultimate commercial viability. Stay abreast of markets and commercial potential, however, in order to set pricing policies that optimize the isotope supply with limited yearly appropriations. Establish an Isotope Review Panel to assist with annual decisions on which isotopes to produce and retain.
- Conduct an integrated comprehensive assessment of the current isotope production system. View the national laboratory, university, and commercial sectors as an integrated production system. Create long-term plans for an assured supply of isotopes.
- Establish key partnerships with producers of isotopes. Outsource production to non-DOE facilities to provide flexibility, robustness, lower cost, and achieve other DOE-NE objectives such as education.

Infrastructure

A requirement for producing isotopes is the availability of appropriate facilities, such as reactors, accelerators and hot cells. DOE-NE has a few dedicated facilities for isotope production, but more frequently depends on facilities owned by others to produce isotopes on an incremental basis. The infrastructure relevant to isotope production is aging and declining, which requires continued attention and consideration of new investments by DOE.

(6) Maintain current infrastructure while planning for new capability within the next two decades.

- Increase investments in maintaining and improving the capabilities of existing infrastructure.
- Build new, dedicated isotope production capability and/or undertake major upgrades to existing facilities to meet changing demands, and national and regional needs. DOE-NE should perform a comprehensive assessment of university, laboratory, and international infrastructure as a basis for planning future upgrades or new capacity.

- Establish an appropriately sized, flexible facility for enriching small quantities of stable and radioactive isotopes. Such a facility should be based on the deployment of successful R&D separation technologies established through R&D described in item (2) above.

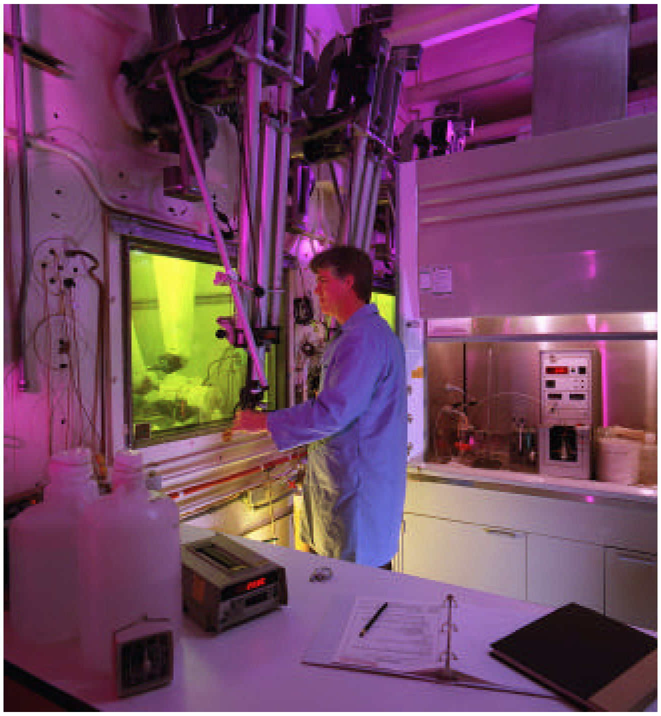


Figure 15. Handling radioisotopes in hot cell at Pacific Northwest National Laboratory's Radiochemical Processing Lab

Waste Management

The existence of facilities to dispose of the wastes generated by isotope producers, researchers, and users is critical to continuation of these activities. Lack of waste disposal has severely curtailed medical services and other isotope activities in the past. While the present DOE Low-Level Waste (LLW) disposal system[5] appears to be adequate to handle wastes from its production and research facilities, the situation regarding civilian LLW disposal and the regional compacts is much more fragile. The primary users of civilian LLW facilities are civilian power reactors and civilian organizations involved in some aspect of the isotope or radiation source enterprise, both of which fall within the programmatic purview of DOE-NE. The DOE project to facilitate civilian LLW disposal is no longer funded.

(7) To alleviate the absence of DOE attention in this area and the possibility of severe impediments in the future, we recommend that this LLW effort be funded and responsibility transferred to DOE-NE, which has a major stake in the outcomes.

---

[5] US DOE, "Record of Decision for the Department of Energy's Waste Management Program: Treatment and Disposal of Low-Level Waste and Mixed Low-Level Waste; Amendment of the Record of Decision for the Nevada Test Site", Fed. Reg. 65(38) 10061-10066 (February 25, 2000).

Education

Education is important to isotope research, production, and application in multiple dimensions. Scientific training is required to understand the fundamental science underlying the chemistry and physics of isotopes (academic education), but technical training on operation of laboratories, reactors, accelerators, and hot cells is equally important. Beyond scientific and technical training, education of decision-makers and the public on the benefits, costs, and risks of isotope production and use is necessary to foster support.

(8) DOE-NE should lead a national dialog on technical education requirements related to isotopes and nuclear technology leading to establishment of an educational paradigm appropriate for the future, while continuing to support nuclear science and technology education in the interim.

(9) DOE-NE should lead efforts to educate decision-makers concerning the beneficial uses of isotopes and radiation.

Funding

To support these strategies, the following funding is estimated to be required:

- Isotope R&D: Increase DOE-NE research funding to $10M/yr over the next five years to identify new applications of isotopes and radiation sources. This funding should be primarily focused as specified in the previous section to complement the large amounts of funding NIH and DOE-SC devote to medical applications.
- Production and Inventory: Increase the DOE-NE isotope production and inventory budget by $10M/yr to support efforts to produce research isotopes and to refurbish and upgrade the existing isotope production and inventory infrastructure.
- New Infrastructure: Beginning in FY-2001, fund a $2M/yr evaluation of existing isotope-related supply, demand, and infrastructure leading to a design and budget request by 2003 for a new and/or upgraded isotope production and inventory complex. The cost of the complex could be about $250M, but this value could change substantially depending on the scope of the complex that will not be known until the evaluation is complete.
- Isotope Leadership: Immediately fund a DOE Isotope Leadership Office at $1M/yr and sustain it at this level, adjusted annually for inflation.

All of these amounts are in addition to funding that will be required to assume responsibility for maintaining national resource materials obtained from other organizations. The amount of this new funding cannot be estimated until a decision process and criteria for retention of national resource materials is established and implemented.

V. SPACE NUCLEAR SYSTEMS

DOE and its predecessor agencies have a long history of developing and providing nuclear power systems and technology for a wide variety of civilian space missions. Specific applications have included radioisotope thermoelectric generators (RTGs) in earth orbit and for the Apollo program in the 1960's; the power generators for the recent Cassini mission; and radioisotope heater units (RHUs) for both Cassini and Mars Pathfinder missions. Reactor power programs included the SNAP program in the 1960's and the SP-100 and Multimegawatt programs of the 1980's. Nuclear propulsion programs included the ROVER and NERVA programs in the 1960's and the SDIO Space Nuclear Thermal Propulsion (SNTP) program in the 1980's. As NASA begins to plan more ambitious missions, it is important to assess the potential application of a broader range of nuclear energy sources for civilian space missions. These include further developments of the following:

- Advanced radioisotope power systems to increase the operational efficiency of the units to reduce the demand for the radioisotope Plutonium-238 (Pu-238), used to fuel these systems
- Space nuclear power reactors to provide long-term operational electricity to enable missions requiring significantly more power than possible from conventional means (including chemical, batteries, and solar) or where conventional means are impractical, for instance in the case of a lack of sunlight, and
- Nuclear reactors for direct propulsion applications.

Figure 16. Heat pipe fission reactor research for space applications is ongoing at Los Alamos National Laboratory

The discussion here specifically excludes defense missions that potentially could benefit from similar uses of nuclear technology. There may be many such missions that would be enhanced or enabled by nuclear technology, and they only increase the viability of space nuclear technology applications.

A number of important barriers currently exist to further implementation of nuclear technology to space applications. These include public acceptance of launching nuclear systems into space. The recent controversy over the Cassini mission demonstrated this opposition. Another barrier to extending nuclear applications to space is the cost of developing a space nuclear system. The cost of developing a flight-qualified space nuclear reactor power system will be substantial. Finally, ground testing of space nuclear power and propulsion systems that includes full-up system testing will require modifying existing and/or constructing new facilities which will raise issues regarding both public acceptance and cost.

DOE retains the unique position within the US Government of being the only agency where space nuclear power systems are developed. NASA and the Department of Defense (DOD) will remain primarily users of developed systems with important roles to play in defining the missions and capabilities that they require, but cannot be expected to take on the task of developing these systems. Current practice is for DOE to work with NASA to assure that NASA supports mission specific development and hardware fabrication, while DOE focuses on sustaining the unique program and facility infrastructure that is essential to be able to produce these power systems. NASA’s 1997 Design Reference Mission for Human Exploration of Mars stated that for surface power only a nuclear reactor power source can concentrate sufficient energy in a reasonable mass and volume. It further stated that high-performance propulsion is found to be an enabling technology for a human exploration program and recognized the higher propellant utilization efficiency that nuclear thermal propulsion can provide. In advance of a potential future human exploration mission, NASA is continuing its robotic exploration activities, and is exploring plans to establish and maintain a permanent robotic presence on Mars, which may require long-lived systems and demands for higher power for deep drilling and other operations. Once the full identity of the NASA programs are established, human exploration missions may require both nuclear propulsion and nuclear reactor electricity.

Although there are presently no specific requirements for the first reactor unit, it is recognized that the time required for developing a space nuclear reactor system is longer than the time required to identify and develop any particular mission, and thus an ongoing base technology program that would be independent of specific mission requirements is needed. This would require a government commitment to support such a program. As with many space applications, space reactor programs could have spin-offs for land-based systems, including advanced instrumentation and control, autonomous operations, high performance materials, and advanced energy conversion.

Space nuclear power also has been very attractive to students. These programs will engender a significant amount of excitement in young people and attract them to nuclear science and engineering fields. The issues tend to capture student imagination and generate a palpable level of excitement in the intersection between careers in nuclear and space technologies.

Current activities in space nuclear power are limited almost entirely to radioisotope systems with very little current activity related to space fission systems. This clearly is not sufficient to adequately develop the technologies and systems. There are current activities to continue to supply RTGs and RHUs for NASA-identified missions, however there are considerable concerns about the reliability of the supply of the Pu-238 heat source material. There currently is no domestic production capability for Pu-238. The United States presently contracts with Russia for Pu-238. There have been discussions recently on re-establishing a domestic Pu-238 production capability. Production of Pu-238 is under consideration for the advanced test reactor (ATR), the high flux isotope reactor (HFIR), commercial LWRs, and the fast flux test facility (FFTF). Hot cell facilities located near the DOE reactors also are being considered for the processing activities associated with Pu-238 production. Recent space nuclear power activities in DOE also have included limited work on power conversion efficiency enhancements, including further development of Alkali Metal Thermoelectric Energy Conversion (AMTEC) technology and Stirling engine refinements.

Research Strategies

A broad set of research needs are essential to make space nuclear power and propulsion systems possible. First, there is a need to continue development of radioisotope systems to ensure their availability for future applications. Radioisotope power systems and heater units will continue to have important functions in space and reliable Pu-238 supplies will be essential. There are some concerns about depending on Russian supplies of Pu-238 as long-term reliability is uncertain and this might be viewed as supporting a production scheme that is counter to US environmental and proliferation goals. The critical issues in radioisotope power systems are ensuring the stability of the Pu-238 fuel supply and the development of reliable power conversion schemes that decrease Pu-238 requirements by increasing the power conversion efficiency. Early studies should be established to evaluate alternative methods for Pu-238 production, including thermal spectrum production schemes in light water reactors and research reactors and in fast spectrum production in FFTF and other devices.

Second, there is an important need to establish a continuous technology research and development program focused on providing the fundamental understanding of the broad base of technologies that may be needed for a wide range of missions for both radioisotope and reactor power systems. Because all of the possible missions cannot be predicted in advance, it is important that a technology development and improvement program be established. Some of the research areas include fuel and heat source materials, high temperature and lightweight materials for shielding, neutron moderators, power conversion, and heat removal systems.

Third, specific reactor systems for electrical power production under varying conditions for nuclear electric propulsion and surface power need to be developed. This program should be directed toward developing a flight-qualified fission electric power system in the 5 - 50 KWe range that would be suitable for power production and nuclear electric propulsion (NEP). It is clear that the goal of this program is to develop a flight-qualified system and that the first space nuclear flight system must be safe, reliable, ground-tested, and simple to ensure success. It also should be recognized that it will probably be necessary to use high fissile content uranium (using U-235 or U-233) to get a low-weight reactor.

Fourth, further developments in the technology and systems required for direct thermal propulsion are needed. The goal of this program would be to establish the technology for a nuclear thermal rocket (NTR) fuel element with characteristics of 5-30 MW/l power density and 3000 K outlet temperature. This will require a high power density testing capability (with an estimated neutron flux on the order of 10^{16} n/cm^2-sec) and would primarily validate the fuel's mechanical design for prototypic values of temperature, temperature gradients, pressure, and flow rate.

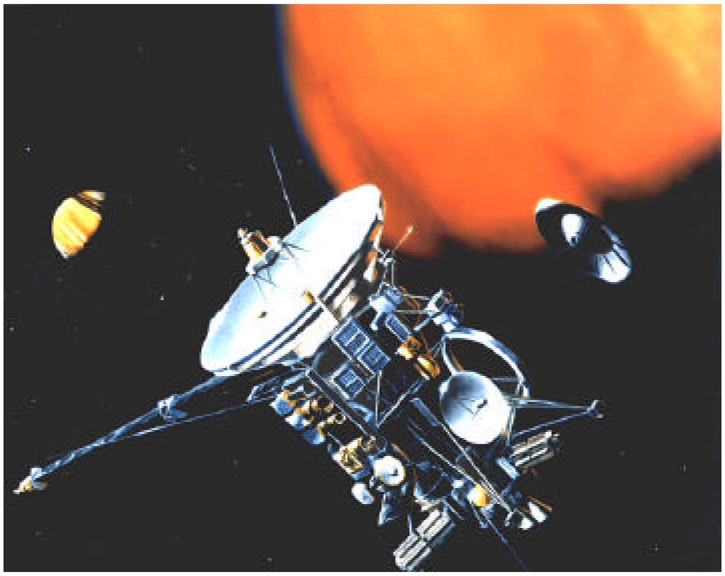


Figure 17. Artist's concept of Cassini spacecraft, launched in 1997 on a mission to explore Saturn. Cassini uses several Pu-238 radioisotope thermoelectric generators and heat sources.

The following general goals for space nuclear power systems are proposed:

- Establish a DOE policy to support space nuclear power and propulsion systems.

- To support this policy, it is important to establish a base technology development program including areas such as:
  - Advanced fuels
  - High-temperature, lightweight materials
  - High-efficiency low-mass radiators and heat removal systems
  - Instrumentation and control systems, including significant developments in highly reliable autonomous control
  - Power conversion systems and technologies
  - Safety systems
  - Core cooling technologies and components
  - Protective coatings for fuels, structural components, and nozzle throat
  - Lightweight radiation resistant moderators and shielding materials
  - High-temperature NTR components

- The following system development and production goals should be considered for 2010-2015, or earlier:
  For advancing radioisotope power systems:
  - Establish an assured supply of Pu-238.
  - Double the efficiency of current power systems.
  - Provide radioisotope systems to meet a wider range of power levels.

For development of space reactor systems for both electricity production and propulsion:

- Demonstrate a flight-qualified fission electric power system (5 - 50 KWe) suitable for power and nuclear electric propulsion.
- Demonstrate the performance of a nuclear thermal rocket fuel element (a minimum of one) with characteristics of 5-30 MW/l power density and 3000 K outlet temperature.
- Develop plans for full-scale testing capability in space for an NTR.

Funding

It is difficult to estimate the resources necessary to reach the above objectives without a complete plan for development. However, estimates can be made on the approximate totals for steady state funding levels in each of the target areas. It is estimated that the space radioisotope power system research, development, and production activities will require between $150M to $200M over a 10-15 year time period. The space electrical power reactor research and development program is very roughly estimated to require on the order of $1 B to develop a flight qualified system, and the nuclear propulsion program will need an investment of approximately $1 B over a similar period of time. Utilization of previously developed space nuclear power and propulsion facilities and collaborations with basic nuclear science and engineering activities discussed in other sections of this report for development and testing can temper some of these expenses. Of course, these cost estimates depend strongly on the assumptions for the design and degree of ground testing required. Facility costs will depend on whether new or modified facilities are needed. A continuous technology research and development program funded annually at the $25 M level would provide a fundamental understanding of the broad base of technologies needed for a wide range of missions for both radioisotope and reactor systems. It must be noted that no comprehensive system development cost analysis has been done recently for any particular system. Until such studies are conducted, the above cost estimates must be considered to include fairly sizable uncertainties. Development and facility studies and evaluation should be a primary DOE objective in the area of space nuclear power development.

Facility and infrastructure items

Although this section did not focus on facility requirements, some facility requirements were identified:

- Infrastructure for Pu-238 supply.
- Management of waste stream from Pu-238 production.
- Glovebox, hot cell, analytical, and laboratory facilities for technology development employing Pu-238 and space nuclear fuels.
- Test reactor to simulate NTR power density and mission profile with an appropriate test position for testing single fuel elements of different design. This reactor also could be used to test the next generation steady state source reactor and isotope production reactor elements. An early examination is needed to establish the capabilities and requirements for the NTR fuel element testing to ascertain whether any existing reactor facilities, such as FFTF or ATR, could be used for this testing.

- Previously developed facilities should be considered for re-utilization to reduce the overall cost of development and testing for the space nuclear power program.

VI. IMPLICATIONS ON THE NE PROGRAM OF OTHER KEY DOE NUCLEAR ENERGY MISSIONS

DOE has many other activities in the nuclear energy area, some of which involve NE and others that do not. This first effort at a long range R&D plan does not attempt to include these other areas. However, in this section several of these areas are discussed because of their potential impact on or involvement with the R&D programs recommended in the other sections of this report.

Waste Management: Worldwide, the disposal of radioactive waste is a difficult challenge. Nowhere has this become more evident than in the United States. One of the workshops for this R&D plan discussed four types of radioactive materials: high level waste (HLW), defense wastes, surplus fissile weapons material, and low level waste (LLW).

High level waste includes the most radioactive waste as well as some extremely long-lived materials. This category includes commercial spent fuel and several types of government material from nuclear weapons production, naval reactors, and research reactors. Resolving the disposition of HLW is essential both for the clean-up of the legacy of nuclear weapons production and to the DOE mission of maintaining nuclear power as an integral part of the US energy portfolio.

Some of the associated issues require policy decisions:

- agreement on what is interim storage, enabling DOE, states, and owners of nuclear power plants to develop plans for stored HLW;
- DOE taking title to commercial spent nuclear fuel; and
- DOE becoming an active participant in an international cooperative organization to address what to do with commercial spent fuel.

New technologies may improve the engineered package design for use in repositories through containers with longer lifetimes before failure and methods to demonstrate containment times. Transmutation technologies utilizing reactors or accelerators (ATW) may provide long term improvements in spent fuel disposition.

DOE has major programs (about $5 billion/year, estimated to last past 2050) addressing the legacy of decades of nuclear weapons production. While environmentally very important, and requiring substantial research (e.g., the Environmental Management Science Program), this is not an area included in this nuclear energy R&D plan. Perhaps the most important point is that all future nuclear energy programs should include a focus on environmental protection from the beginning of the programs.

Regarding nuclear power, the current central focus in the United States (and of growing concern in such countries as Germany, the United Kingdom, and Japan) is how to develop permanent repositories for spent fuel or waste from reprocessing operations. While these issues have been a major part of discussions on the future of US nuclear power, this long-range R&D plan assumes these issues will have been resolved by the period 2010-2020, the focus time period for this plan.

DOE has a program, funded at more than $300 million/year, addressing geologic disposal at Yucca Mountain. This R&D plan does not address the Yucca Mountain effort.

ATW: The program for accelerator transmutation of waste is now in NE. A recent DOE roadmap report presented a six-year research program for $280 million – a substantial program. Interest is not confined to the United States. Sizable programs exist in the European Union and Japan. Although at this size the ATW could become the major NE program, it is not included in this R&D plan both because the planning has been laid out in the roadmap report and, if successful, the program would be for waste management.

Materials Disposition: As part of the programs to reduce the nuclear arsenals of the United States and Russia, substantial amounts of HEU and weapons-grade plutonium are being recovered from dismantled nuclear weapons. The HEU can be blended with depleted uranium to produce low enriched uranium to use in making fuel for nuclear reactors. The plutonium poses more difficult problems. The United States and Russia have agreed to pursue a dual-track, or hybrid, approach in which two approaches are examined for plutonium disposal, immobilization (in glass or ceramic logs) and use in mixed-oxide (MOX) fuel. There also is a collaborative effort with Russia and France, sponsored by DOE-MD, to develop a gas-cooled reactor to burn Russian weapons plutonium.

DOE programs for disposal of excess weapons materials are extremely important for national security. However, they are not included in this R&D plan. There are reactor-related issues: the safety of reactors using MOX fuel and the possible design of new fuels and even new reactors. However, the DOE has at least two programs addressing the associated issues (the NERAC TOPS task force and the materials disposition program) as well as several joint U.S.-Russian programs.

Naval Reactors: Finally, perhaps the most successful U.S. reactor program is the naval reactors program. For more than forty years, this program has developed propulsion systems for the U.S. Navy, including surface ships and submarines. The performance and safety records of these reactors have been outstanding. Continued improvements can be expected from this program. None of these efforts are included in this R&D plan since the program is unique and classified.

Figure 18. USS Seawolf (SSN 21), the Navy's newest fast attack nuclear powered submarine. (Photo courtesy of Electic Boat)

VII. INTERNATIONAL

All R&D programs can benefit by international participation and coordination, including exchange of information and use of facilities and sharing funding. While not conducting an exhaustive review, some existing and potential international elements in each are summarized in the following.

Basic Science and Engineering Research

Some of the research discussed in Section II may involve new facilities, and collaboration with the international community may be needed. International collaboration and cooperation have always been strengths of the scientific community, but will need to be enhanced. Significant research is being conducted in other countries, for example, in Europe and Japan. Although databases exist, it is sometimes difficult to gain access to them due to proprietary or other interests. An important limitation on collaborative activities, under the currently very small funding levels for US researchers, is that they have very little to “bring to the table.” International collaboration will require suitable levels of research support in the United States. Applied technology limitations on the dissemination of information related to advanced reactors is a substantial barrier to international collaboration. The applied technology limitations should be revised to reflect the U.S. Government’s need to collaborate freely internationally to leverage the modest U.S. investment or to gain access to more advanced foreign technology.

Nuclear Fuels

Although nations may not fully agree on a particular approach to reactor or fuel cycle technology, collaboration on advanced fuel cycle R&D programs of the type envisioned can enable common ground for collaboration. International participation should also be sought because the expected costs of a program would be sufficiently high that non-U.S. contributors (who would benefit from the results of the program) may be needed to share costs. Also, it will be necessary to capitalize on knowledge, data and existing research reactor and hot cell facilities, internationally. Therefore, it is recommended that DOE aggressively pursue appropriate international collaboration at the earliest stages of designing the advanced fuels/fuel cycle R&D program.

I&C

International work on advanced I&C and the underlying technologies for nuclear power plants is extensive. Japan, France, Korea, and Taiwan are currently building new power plants and have large programs of R&D on advanced I&C associated with these plants and future generations. Canada and England have recently completed large nuclear plants and have active programs of R&D looking at such issues as design methods and how to review and assess complex, advanced control and monitoring systems. In addition, DOE's International Nuclear Safety Program is sponsoring work to upgrade I&C systems in power reactors in the former Soviet Union to improve safety and meet international standards. The U.S. Nuclear Regulatory Commission has issued new guidance for digital I&C systems in nuclear power plants, and these rules are being utilized by the Koreans and Taiwanese in their new plants. Continued international cooperation and collaboration is important, to share knowledge of the current technology, to assess and improve regulations, and to leverage investments through cost sharing.

Reactor Technology

The international community is heavily involved in research and development for advanced nuclear energy systems. The European Union developed the European Pressurized Water Reactor (the equivalent of the United States large ALWR plants). Japan is leading the world in development and application of Advanced Boiling Water Reactors. European and Japanese utilities are working with US firms in the development of passive PWRs and BWRs at higher unit power levels (1000 MWe) than the present US certified 600 MWe design. Japan is also initiating startup of a new high temperature gas-cooled reactor. Russia is developing an advanced PbBi cooled fast reactor with its associated fuel cycle, and is cooperating with the United States and France in the development of a high temperature direct-cycle gas-cooled reactor. South Africa is embarking on an ambitious Pebble Bed Gas-Cooled Reactor program. China is building a small Pebble Bed Reactor research facility. France, Japan, and the UK are engaged in R&D to support reprocessing of plutonium and uranium in spent fuel and to use these materials in mixed oxide fuel (MOX) in existing LWR plants.

Isotopes and Radiation Sources

The United States would benefit from the establishment of a policy for reliance upon international providers for selected isotopes. It is not desirable to rely upon foreign sources of isotopes indefinitely, as changes are possible not only in foreign relationships, but also in national priorities of the foreign suppliers. Assured supplies are a requirement in many cases. Balance is needed between the critical nature of the demand and the degree of dependence upon foreign suppliers. The United States could also re-examine possible new areas of isotope exports to support its own infrastructure for isotope production and research.

Research and production of isotopes represents a fertile area for international collaboration. The United States may provide international leadership in this area by filling the following roles:

- Infrastructure and facilities coordination of stable isotope, radioisotope, and irradiation facilities to meet national and international demands.
- International clearinghouse for isotope and irradiation facility information, through provision of a tracking function in the leadership activity relating to isotope production and irradiation facilities. As a result of this activity, the United States may identify areas for which the United States can become a supplier as well as areas where the United States may safely rely upon foreign sources and research, in addition to the identification of areas of joint endeavor.
- International isotope conferences at the government level: The United States could initiate these to assure continuation of coordinated joint and individual efforts.

Space

Based upon the significant programs in the past in both the U.S. and Russia, a joint program in space nuclear power and propulsion technology development may be sensible. Links between these programs were forged during the late 1980's and early 1990's that could be extended to rapidly benefit this technology development effort. This could be especially advantageous in the testing and facility development area to reduce the costs required for space nuclear power development activities. Another intriguing aspect of this activity could be the coordination of space nuclear power and propulsion efforts with the Nuclear Cities Initiative operated by the National Nuclear Security Agency to creatively utilize the nuclear systems and development capabilities that exist in Russia. A worldwide collaborative effort that also includes European and Asian space programs also could be pursued. International collaboration on major development programs will require addressing various issues including the exchange and verification of safety related data, reaching agreements on the exchange of technical information, provision of facility information to support environmental assessments, and policy decisions regarding the extent of domestic versus international development of advanced nuclear technologies.

VIII. FUNDING

It is not difficult for the research community – in any discipline – to generate a lengthy list of projects. Similar to another aphorism, proposed research can expand to fill any budget. However, after substantial thought and discussion, the participants in developing this R&D plan narrowed the desirable projects to those judged to be most important. No efforts were made to retain "nice to do" projects. Also, the plan attempts to be realistic by not exceeding what might be possible, while using as a floor what is necessary if the goals outlined here – education, infrastructure, vital research – are to be achieved.

The approach used to develop a budget was to estimate what annual funding would be necessary in 2005 for the programs described in the preceding chapters. Recognizing this would require a ramp-up from current funding, the amounts are judged to be well within reason for the Department of Energy and, to a lesser extent, science business lines. The 2005 funding level is assumed to be stable at least at that level, as well as recognizing that some programs would require a decision (in 2010 or later) as to whether to commit larger funding amounts for full scale development and possible prototype construction.

In developing this plan, several fundamental assumptions were made:

- We estimate that the programs recommended here would be above a nuclear energy R&D base of what is currently about $55 million per year. Funds recommended are new monies, not reprogrammed from other related efforts.

- The research work cannot go forward without facilities, researchers, and students. The research would provide a foundation for funding these other elements, but without these other elements present, the research could not be done.

As is clear from several of the sections, focusing on a single year, 2005, neglects the difficult issues associated with how to ramp up as well as not addressing the longer term commitment. However, taking a one-year cut does enable comparison with current funding to give an initial reality check.

We also include a lower total level, not because we believe there is excess in what is estimated here, but because policy makers may decide this is too ambitious a program. Since the items listed here were deemed to be most important in each area, further reductions should assess priorities across areas, for example, by deciding which missions of DOE should not be supported.

This plan estimates the following funding in 2005 (based on FY2000 dollars) if the programs described in this report are to be accomplished:

Area	2005 R&D Funding Need (FY00$, in millions)	Comments
Science and Engineering	60	
Advanced Fuels	42	Includes $20M for TREAT and $10M for ATR
I&C	30	
Nuclear Power	60	
Isotopes	23	Does not include funding for a new facility
Space Nuclear R&D	25	
Total:	$240M in FY 2005	

This total, $240 M, is to be compared with the current programs in these areas, about $55 M, indicating a doable increase. If a reduction is necessary, a level of $150 M in 2005 would be our recommendation, but what should be eliminated from the above would require a review of all priorities. In all cases, we are recommending new monies, not a transfer. Also, we have concentrated on the levels to be achieved by 2005. To reach these levels efficiently will require a ramp up beginning in earlier years.

The above does not include the system development costs associated with a revitalized space nuclear power program. A program designed to achieve the ambitious long-term system development goals identified in this report is estimated to cost $170 M in 2005, but is based upon a set of national policy decisions. Hence, here it is treated separately. A national policy decision on human exploration missions will have a major effect on the need for advanced space nuclear systems. However, future deep space and robotic planetary missions are likely to drive the need for system improvements that are dependent upon new advances in technology. Current funding for mission specific system development efforts is provided by the mission sponsoring agencies. Consideration should be given at least to establishing a sustained level of R&D for this technology area apart from current generation or future system development efforts and facility infrastructure costs. An annual base technology R&D funding level of $25M for space nuclear technology, separate from the more costly full system development goals that dominate the $170M estimate, is included in the funding figures above. This $25 M is directed at maturing technologies to the point where they may result in improvements to current generation systems or be incorporated into new system development programs having reduced technology development risk.

IX. GENERAL COMMENTS

Embedded in this plan are several major policy issues:

- What is the role of the federal government in funding research where there is an existing industry? This pertains both to nuclear power and to isotopes. Consistent with U.S. Government policy in many other areas (e.g., fossil energy research), we assume there is a definite responsibility to assure that research be funded that is important for the U.S. and where it is unlikely that industry will fund it.
- What is the role of DOE in ensuring that nuclear power remains a major element in the U.S. energy portfolio? We assume that is a DOE responsibility.
- What is the responsibility of DOE to ensure that a supply of qualified personnel be available to handle the many tasks associated with the application of nuclear energy? We assume that is a DOE responsibility.
- What is the responsibility of DOE to ensure that necessary facilities be maintained at universities and national laboratories to both perform research and to educate students? While another NERAC group is examining what those needs would be, we do assume this is a DOE responsibility.
- Finally, what should be the future role of nuclear power in space exploration? We make no assumption on this issue.

We strongly urge that funding be included in the budgets to reach the level of $240 million in 2005. For the reasons outlined in the summary, this would be a wise investment for the future.

Appendix A

Working Group Report on – Space Nuclear Power Systems and Nuclear Waste Technology R&D

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Nuclear Waste Technology and Space Nuclear Systems R&D
Working Group
October 18-20, 1999 Workshop

NERAC Subcommittee on Long-Term Nuclear Research and Development Planning
Workshop I Report
Oct. 18-20, 1999

INTRODUCTION

"Even though one cannot anticipate the answers in basic research, the return on the public's investment can be maximized through long-range planning of the most promising avenues to explore and the resources needed to explore them." (p. v) "Pursuit of this goal entails developing new technologies and advanced facilities, educating young scientists, training a technical workforce, and contributing to the broader science and technology enterprise?." (p. vi)
Ref:: "Nuclear Science: A Long Range Plan", DOE/NSF, Feb. 1996.

The purpose of this effort is to develop the first iteration of a long-range plan for nuclear energy in the Department of Energy. It is desirable to update, expand, and improve this plan every few years. The focus must NOT be on next year's budget nor that for the next few years. Rather, the focus is on what is necessary to develop over the next 10-15 years. The approach to be taken is to begin with DOE as a whole, then narrow to NE.

Working Group 1 Summary Report
Nuclear Waste Technology and Space Nuclear Systems R&D

This group addressed long-term planning for disposition of radioactive materials, development of space nuclear systems, and general needs related to these areas. The following are the conclusions and recommendations from the two days of discussions. In addition, specific comments from the discussions are included to provide amplification of the conclusions and recommendations.

Although the conclusions and recommendations are not in all cases a consensus, they are in every case the view of a large majority of the participants.

CONCLUSIONS AND RECOMMENDATIONS

Four types of radioactive materials were addressed by the working group: High Level Waste (HLW), Defense Wastes, Surplus Fissile Weapons Material, and Low Level Waste (LLW).

I. High Level Waste (HLW)

This radioactive material includes the most radioactive of the waste as well as some extremely long-lived materials. HLW includes commercial spent fuel, although there is not agreement that this is purely a waste, and several types of government material from nuclear weapons production, naval reactors, and research reactors.

Goals for 2010-2015:

1. The Yucca Mountain geologic repository will have received an NRC license to operate.
2. Agreement reached on what is interim storage, enabling DOE, states, and owners of nuclear power plants to develop plans for stored HLW.
3. Technologies developed that would reduce the required time for proof of containment in a repository.
4. Consistent with the Nuclear Waste Policy Act, title to all commercial spent nuclear fuel (SNF) transferred to DOE.
5. Operation of a pilot plant to do partitioning.
6. Proof of principle completed for transmutation approach for use in ATW program.
7. An integrated ATW demonstration facility under construction to use a 10 MW accelerator.
8. DOE active participant in an international cooperative organization to address what to do with commercial spent fuel.

Accomplishing these goals will require some new technologies and overcoming some existing barriers.

New Technologies Required:

1. Waste packaging for repositories:
    (a) Containers, with longer lifetimes before failure.
    (b) Methods to demonstrate the containment times required for the desired container performance.
2. Partitioning technologies:
    (a) At the front end, probably aqueous, with controls to prevent diversion of separated material usable in nuclear weapons and to reduce the production of secondary waste.
    (b) Technologies for bulk processing, for example, pyroprocessing.
3. Transmutation technologies, of which the most prominent is ATW.

Barriers (or Challenges):

1. The standards for disposal are not yet established.
2. International collaboration will be difficult because of commercial proprietary information and sensitive nuclear information.
3. Complex regulations governing disposition.

NE Responsibilities:

1. NE is responsible for development and implementation of technologies for waste materials for disposal . Thus, NE is concerned with partitioning, transmutation, and waste form, but not for the container or for emplacement into a repository.
2. NE will be responsible for the ATW program.

II. Defense Wastes

Transuranic (TRU) defense wastes are being emplaced in the WIPP facility in New Mexico. There remain a large amount of other defense wastes in tanks, in fuel pools, in other storage, and in facilities to be decommissioned.

Goals for 2010-2015:

1. Program developed to dispose of Navy SNF, taking into consideration it includes highly enriched uranium (HEU).
2. Remove the dissolved radionuclides from tanks at Savannah River.
3. Remove all radioactive materials from and clean up the Hanford K basins.
4. Technologies developed to remove more effectively and completely all the radioactive materials from all waste tanks.
5. Implement monitoring systems at all appropriate DOE sites to identify the extent and the movement of sub-surface contamination.
6. Remove all SNF from Hanford storage basins and select treatment process(es) for disposal.
7. Develop plans to handle all defense HLW, including those currently without defined disposition paths, i.e., that HLW currently "without a home".
8. Implement a comprehensive inventory system that includes all forms of defense wastes, using consistent methodologies and having reconciled records.

Technologies required:

1. Because significant amounts of radioactive materials from nuclear weapons production processes have caused subsurface contamination, technologies are needed to immobilize wastes in deep subsurface regions.
2. Treatment processes to enable disposal of the damaged, corroded, and leaking SNF at Hanford.

NE Responsibilities:

NE does not have responsibility for defense wastes, but should offer technical assistance and propose any pertinent technologies developed in NE programs

III. Surplus fissile weapons materials disposition

As part of the programs to reduce the nuclear arsenals of the United States and Russia, substantial amounts of HEU and weapons-grade plutonium are being recovered from dismantled weapons. The HEU can be blended with depleted uranium to produce low enriched uranium to use in making fuel for nuclear reactors. The plutonium poses more difficult problems. The US and Russia have agreed to pursue a dual-track, or hybrid, approach in which two approaches are examined for plutonium disposal: immobilization and use in MOX fuel. There also is a collaborative effort with Russia and France, sponsored by DOE-MD, to develop a gas-cooled reactor to burn Russian weapons plutonium.

Goal for 2010-2015:

Dual track disposition program underway in the United States and a similar program underway in Russia.

NE Responsibilities:

1. NE should be involved in oversight of the programs to manufacture and review the performance of the MOX fuel and in the performance of the reactors to be used for the MOX program.
2. NE should follow the development of the Russian gas-cooled plutonium-burning reactor.
3. NE should examine whether the materials from the dismantled weapons have uses in research.

IV. Low-level Waste (LLW)

After more than an hour of discussion, the participants did not come to a conclusion as to whom is responsible for addressing the LLW issues. However, there was agreement that these issues needed to be addressed.

Goals for 2010-2015:

1. Reconsider what is defined to be LLW by removing high-activity waste from inclusion and considering excluding materials currently included at the lower limit.
2. Complete analyses of technologies that might provide solutions to LLW disposal problems.

Technologies required:

Waste minimization technologies.

In a lengthy discussion, some participants argued that technologies to separate LLW constituents could reduce the hazards associated with LLW sites and make such sites acceptable to the public. Other participants strongly disagreed.

NE Responsibilities:

NE should lead DOE efforts toward proposing solutions to LLW disposal problems.

V. Space Nuclear Systems

DOE has provided nuclear power systems for many space missions, including power generators for the recent Cassini mission and heaters for both Cassini and Mars Pathfinder missions. However, as NASA begins to plan more ambitious missions, it is useful to assess the potential application of a broader range of nuclear energy sources for non-military space missions.

General goals for space nuclear power systems in 2010-2015

1. Establish a DOE policy to support space nuclear power and propulsion systems.
2. To support this space policy, establish a base technology development program which includes:
    a) Development of advanced fuels.
    b) Development of high-temperature, light-weight materials.
    c) High-efficiency low-mass heat radiators.
    d) I&C systems.
    e) Power conversion systems
    f) Improved safety of systems..
    g) A range of radioisotope systems with greater efficiency.
    h) Development of protective coating materials and techniques for fuels, structural components, and nozzle throat.
    i) Light weight radiation resistant moderators
    j) High temperature turbine to operate at NTR outlet temperatures in a radiation field.

Goals for radioisotope power systems for 2010-2015:

1. Double the efficiency of current power system(s) with a range of technologies.
2. Establish an assured supply of Pu-238.
3. Provide radioisotope systems to meet a wider range of power levels.

Goals for space reactors in 2010-2015:

1. Demonstrate a flight-qualified fission system (5 - 50 kWe) suitable for power and nuclear electric propulsion (NEP).
2. Demonstrate the performance of a nuclear thermal rocket (NTR) fuel element (minimum of one) with characteristics of 5-30 MW/l power density and 3000 K outlet temperature.
3. Plan for full-up testing capability for an NTR.

Space reactor technologies required:

Fuels, materials (high temperature/light weight), shielding, core cooling technologies/components (e.g., thermal-hydraulics, heat pipes, pump, compressor), safety devices/analyses, energy conversion technologies, radiator/heat removal systems.
NEP technology selected to maximize performance, minimize weight, and maximize energy conversion, recognizing it may be necessary for trade-offs among these criteria.

Barriers to space reactors:

1. Public acceptance of putting nuclear systems in space. The controversy over the Cassini mission demonstrated the opposition.
2. Cost of a space nuclear system may be prohibitive.
3. To accomplish full-up testing may require building a new reactor, with both public acceptance and cost major challenges.

Submitted comment: an NTR development could test single fuel elements in a suitable test reactor (initially in TREAT, and eventually in a new test reactor). This test would primarily validate the elements mechanical design for prototypic values of temperature, temperature gradients, pressure, and flow rate. In parallel with this test an integrated engine test (including everything except the reactor) could validate the simultaneous operation of the turbo-pump assembly, thrust vector control, propellant management system, nozzle cooling flow control, etc. on a stand in which the reactor response is added by a simulator. Similar techniques are used in the aerospace industry to test systems for new aircraft (planes or missiles) prior to doing a full flight test. This approach would be less expensive, and would not be “full-up” . The final flight test could be done in space.

VI. General Needs

A department-wide need is for integration across DOE of planning and programs for issues related to nuclear energy.

An NE need is to increase teaming with international organizations and with universities.

VII. Some facility requirements

Although this workshop did not focus on facility requirements, participants in this session did identify some facility requirements as part of the discussions on the waste and space issues.

1. Facilities for steady state (fast spectrum) and transient irradiation testing to be used for both ATW and space programs. A very high flux reactor facility will be required for full-up testing of a prototype NTR fuel element.
2. Hot cell facilities for remote characterization of irradiated fuels and materials and radioactive waste materials. These would be useful for ATW, HLW, and space programs.
3. Accelerator and spallation target facilities for the ATW program.
4. Facilities for proof-of-principle testing, including pilot-scale fuel processing for the ATW concept.
5. A demonstration plant for an ATW system.
6. Infrastructure for Pu-238 supply.
7. Glovebox and laboratory facilities for technology development employing actinides.
8. Test reactor to simulate NTR power density and mission profile with an appropriate test position for testing single fuel elements of different design. This reactor could also be used to test the next generation steady state source reactor and isotope production reactor elements.

VIII. Education

This workshop did not address education explicitly, although the topic came up several times in the discussions in this session. One theme was the need for education in nuclear-related environmental issues, for example, establishing nuclear environmental engineering as a discipline. The participants recommended a goal of DOE working with universities to establish curricula to educate students in nuclear environmental technology and issues.

The participants recommended that each NE program allocate at least 2 % of the funds for universities and education.

SOME ***INDIVIDUAL*** COMMENTS: These are NOT consensus statements. They are individual statements included to provide more background for those not at the meeting.

High Level Waste (HLW):

The group expressed the desire for DOE to better integrate its offices for addressing waste issues. There are several offices with some responsibilities, but little apparent coordination among these offices.

Focus on a two-prong approach: develop ATW and aim for a shorter time period requirement for a repository license.

There is a close parallel between commercial nuclear waste and weapons legacy waste.

Spent fuel is not waste. There is a good amount of useful isotopes in SNF, e.g., Pu-238.

Look at alternatives to transmutation, such as an improved waste package. The current OCRWM waste package is designed for 300-1000 years.

DOE should have a transparent and reassuring monitoring system to use with subsurface radioactivity at places like Hanford. Putting a vadose zone monitoring system in is feasible and is part of the EMSP (environmental management science program).

Reprocessing/recycling/processing:

Broad agreement that the implicit/explicit ban on reprocessing should be lifted. The terminology is sensitive. Perhaps better to use recycling or conditioning instead of reprocessing.

Removal of the ban on reprocessing would allow the U.S. to once again participate in international reprocessing technology debates.

It is a mistake not to reprocess SNF. Other countries have not abandoned this option. Effort should be put on proliferation resistant means of handling the SNF.

Conditioning of the SNF to remove the "bad actors" would make it easier to get waste into a repository.

Partitioning of troublesome radionuclides allows for economical packaging using robust forms and packages.

Waste management and systems such as ATW should be viewed as part of a larger context that includes energy production in the next century. Recycle will be a necessary part of the global energy supply, so that the U.S. needs to get its story straight. This would be possible within a proliferation-resistant scheme.

PUREX-type facilities have led to the largest environmental impacts of nuclear facilities and the world inventory of separated plutonium is a major proliferation concern.

If the goal is a deep reduction in the number of nuclear weapons, then reprocessing plants operated by governments, which build stockpiles of separated plutonium, are impediments to reductions of weapons-usable materials. Commercial plants such as THORP and La Hague legitimize national efforts, e.g., Russian, to separate weapons-usable materials.

Yucca Mountain:

YM can be a safe interim storage site.

Any YM license likely will be an interim license. Congress may not be willing to force Nevada to accept HLW, so an ATW system could be an enabling program for YM.
An alternative to Yucca Mountain (YM) should be pursued. This does not require throwing away YM or postponing it until an ATW system is ready. There is a great benefit to getting the first spent fuel assemblies into YM, to show that the waste problem can be solved.

Two approaches could be pursued to address the large and growing inventory of SNF: (1) abandon YM and strive to produce waste that does not need geologic disposal; (2) pursue innovative waste techniques in parallel with YM.

ATW/Transmutation:

Reactor transmutation of waste might be an interesting concept and could be more immediate than ATW. Think of other systems, such as IFR (integral fast reactor) or advanced systems that might be deployed with an ATW system. Even future advanced reactor systems may require an ATW deployment, e.g., one ATW per hundred IFRs, to produce a "clean" waste stream.

Submitted comment: Although there is clearly merit in looking at reactor-based transmutation, there is no reason to believe reactors could be deployed more quickly than ATW. Of the three major technology components in ATW, the accelerator is the easiest and least time-consuming. Much more work is needed for the separations and the transmuter (the part that resembles a reactor). The correct justification for a reactor option is cost, since the accelerator probably adds about 15% to the cost of the system. However, one may need to have the accelerator to safely run on the waste-based fuel. If the fuel has nasty safety characteristics, one may be better off to absorb the cost of the accelerator rather than waste many years trying to license a facility.

Concerns about efficacy or potential of success of transmutation include the required reduction in bulk to make the system worthwhile, the energy required to operate the system, proliferation concerns with the reprocessing stage, and the actinides are not the radionuclides that lead to potential exposures from a repository.

Disagreement with these concerns included that the energy requirement will be met by the ATW system and that non-actinide isotopes, the major concern, would be addressed.

ATW would not be required if nuclear power is not supported. Others disagreed on grounds of waste disposal.

Materials disposition:

Recommend termination of the program to assist Russia in developing an HTGR for Pu disposition. This comment had little support among the other participants.

The proliferation risk today is in stockpiles of assembled weapons and assembled components. Efforts should be addressed toward reducing those risks, rather than on actinides in SNF.

A standard definition of proliferation resistance is needed. Is the "spent fuel standard" acceptable?

Does the United States worry too much about proliferation resistance of waste forms if other nations do not?

Low Level Waste:

The GAO has stated that LLW compacts have not become a successful answer to handling LLW.

Resolving what to do with LLW will be important for continued operation of power reactors and use of medical isotopes.

Should perform a system study of LLW options.

Should do research on radiation safety engineering and health effects of low-level exposure.

DOE should issue guidelines for exposure thresholds.

Space reactors:

Space nuclear power can be very attractive to students.

U-233 would allow a smaller space reactor core. All the U-233 we have should be retained for future space use.

Space reactor programs will have spin-offs for land-based systems.

Space programs will engender excitement in young people.

Space nuclear propulsion is a wonderful fit with the NE mission.

NASA will require nuclear propulsion for a real Mars mission.

The time constant for developing a space nuclear reactor is longer than the mission lifetime, so an ongoing base technology program is needed.

A joint program with Russia would be sensible.

Space nuclear R&D activities should understand that the biggest problem is the cost of development.

The first space nuclear system put up must be clean, safe, simple, and fool-proof to insure success.

NASA should be able to define needs. At the moment, DOE has no specific requirements for the first unit.

The first NEP system should be safe, economic - affordable with optimization with other requirements --, ground-tested, and simple.

The second NTR development will require high power density testing capability (10 e16 n/cm2/sec - TREAT -like capability) and capability for full-up testing.

Perhaps the NTR could be built in a tunnel at the NTS (nuclear test site in Nevada).

It would be best to have a system ready for deployment by 2010.

It will be necessary to use enriched uranium to get a low-weight reactor.

Maintain a technology base program for space nuclear power that would be independent of specific mission requirements. This would require a public commitment to support such a program for when the technology is needed.

Need to explain what is meant by "available". The ALWR has a set of drawings but is hardly available. Need to have hardware, infrastructure that is required to build a system, and be ready for launch to truly have the system available.

RTGs:

RTGs will continue to have their place in space use, but an additional Pu-238 supply will be required.

Some participants were concerned about relying on Russian supplies for Pu-238. The US might be supporting a production scheme that is counter to US environmental and proliferation goals.

Increasing the conversion efficiency will reduce the Pu-238 requirements.

Education:

There is a need to maintain the national infrastructure for nuclear engineering education.

Nuclear engineering needs exciting programs to attract the best and brightest students. ATW won't do it.

NE is getting better at competitive programs, such as NERI, but is not as good at collaborative programs with universities.

Appendix B

Working Group Report on – Medical Isotopes and Industrial Application

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Medical and Industrial Isotope Applications Working Group

October 18-20, 1999 Workshop

Medical and Industrial Isotope Applications Working Group

The NERAC Subcommittee for Long-Term Planning for Nuclear Energy Research and Development conducted a workshop on October 18-20, 1999 in Chicago, IL. This record captures the discussion of a working group on Medical and Industrial Isotope Applications

Subcommittee Charge

The NERAC Subcommittee for Long Term Planning charge began with the following list of key questions:

- What changes should be made to DOE-NE's mission?
- What DOE-NE nuclear energy mission and objectives does this working group's R&D topic area support?
- What should the long-term role of the Department of Energy be in conducting nuclear energy R&D in this topic area?
- What specific R&D (subtopics) should the Department's Nuclear Energy Program focus on over the next decade? Identify any significant drivers for this needed R&D.
- What nuclear energy R&D will be conducted in this broad topic area outside of any DOE involvement?
- What are the challenges or barriers hindering R&D in this topic?
- What should be the order of priorities of these R&D efforts? [Note: While this question was initially posed, it was decided that the breakout groups would not attempt prioritization]

Working Group Discussions

Working group discussions focused on the following items:

- Scope and definition of "medical and industrial applications"
- DOE's recommended mission in this area, challenges in accomplishing this mission, and a recommended long-term vision
- The objectives it would have to pursue to achieve the vision
- The actions that should be considered to accomplish each objective.
- Linkages of the subject area of this working group to higher-level DOE planning documents

Each of these items is elaborated in the following sections.

Scope

The working group decided that the scope of DOE in this topic area is, *"all isotope and radiation science and technology research, development and applications."*

The scope excludes special-use isotopes such as Pu-238, which are considered by other workshops. Note: The term, "isotopes" is inclusive of stable and radioactive isotopes, unless it is specifically called out as, "stable isotopes" or "radioisotopes." Also included are radiation sources such as accelerators and beams.

Mission, Challenges, and Vision

Within the above scope, DOE's *mission* is to lead efforts to use isotopes and radiation to improve the quality of life and economic competitiveness in the U.S.

Major *challenges* to accomplishing this mission were identified as:

- Institutional complexity: Isotopes involves multiple elements of DOE, other Federal agencies, multiple DOE contractors, multiple universities, the private sector, important international players, Federal regulators, and state regulators.
- Economics and benefits not easily measured: The economics of isotopes are not easy to measure because governmental accounting practices are fundamentally different than commercial practices, investment in isotopes comes from multiple sources that are difficult to track, isotope research and production involves multiple use facilities leading to uncertainties in allocation of costs, and some governments subsidize isotope production in use in unknowable ways.
- No central leadership: Despite the widespread believe that use of isotopes is beneficial and the rapid increase in such use, there is no central coordination or leadership of isotope research and production.
- Public perception: Irrespective of the acceptance and growth of isotope use in many medical applications, most of the public still perceives the risks from radiation to be greater than the actuality or the benefits in other applications (e.g., food sterlization). Such perceptions challenge the reliable deployment of isotope uses.
- Maintaining technical expertise: Expertise concerning research, production, and utilization of isotopes is increasingly difficult to maintain. In part, isotope-related areas are not as attractive to new students as other technical fields (e.g., computers) because the latter offers better financial rewards and a better public image. In additition, reductions in financial support for education and related facilities contributes to the decline.
- Deteriorating infrastructure: The facilities (reactors, hot cells, accelerators) used for education, research, and production concerning isotopes and radiation is generally old and reaching the point where maintenance costs are increasing. Superimposed on this, reductions in funding have resulted in some facilities having to be closed, sometimes without consideration of whether it is the best facility to be closed. The absence of central leadership precludes reasoned decision-making in this regard, which is exacerbated by the international dimension.

Given the above mission and the challenges in accomplishing it, the working group stated the following as the desired long-term vision for DOE's isotope and radiation program:

> The DOE is the leader of an enduring, cost-effective isotopes and radiation program with visible public benefits.

Medical and Industrial Isotope Applications Working Group

Objectives

In order to achieve a more specific focus, four major objectives were identified by the working group and are discussed below. Considerations related to international collaboration and facilities were considered under each objective.

Objective 1 -- Support Isotope Research, Development, and Demonstration: Establish a broadened portfolio appropriately balancing RD&D in medical, industrial, life sciences, environmental, agricultural and food safety research, and applications of isotopes and radiation.

Objective 2 -- Production and Inventory: Establish a reliable production, inventory, and irradiation system fully integrated among laboratories, universities, industry, and international isotope producers and/or radiation sources.

Objective 3 B Fostering Applications: Foster implementation of technologies using isotopes and radiation.

Objective 4 B Education: Maintain expertise and build interest in isotopes and radiation applications through a broad-based education program.

Supporting Actions

For each objective the working group used a round-table nominal group technique to develop specific actions that should be considered to accomplish each objective. The results were grouped into subtopics where there were an extensive number of activities, and described in the following sections.

Objective 1 B Support RD&D

New R&D for Applications

1. Conduct R&D on radioisotope delivery systems (such as brachytherapy seeds, etc.)
2. Conduct R&D on new isotopes for microelectronic devices (such as on-chip power supplies, sensor activation, etc.)
3. Conduct R&D on radiation-induced or Benhanced reactions to improve the efficiency or yield of industrial processes.
4. Conduct R&D to reduce radioactive waste streams through radioisotope replacement in applications (such as check sources, etc.)
5. Conduct R&D on non-destructive assay techniques.
6. Conduct R&D on non-destructive evaluation techniques.
7. Conduct R&D on radiation and/or radiation-based detectors, instrumentation and software.

8. Conduct R&D on dosimetry (such as dosimetry for novel beams, high-energy betas, neutrons, etc.)
9. Conduct R&D on regulatory and policy framework for use of isotopes in previously unregulated areas

R&D for Production and Processing

10. Conduct R&D on the production of new, diverse isotopes, as well as higher quality isotopes.
11. Conduct R&D on low-cost separation technologies for both front- and back-end application on the production process.
12. Conduct R&D for new radiation sources (such as accelerators for medical and industrial use, upgrading of existing facilities to meet new applications, equipment for food irradiation, etc.)
13. Conduct R&D on stable isotope production systems.
14. Conduct R&D to create uses for radioactive wastes. Evaluate spent nuclear fuel as a source of isotopes.
15. Conduct R&D on the production of novel isotopes with spallation sources.
16. Conduct R&D to improve the quality of nuclear data (such as cross sections, gamma energy spectra, emission probabilities, branching ratios, etc.)

Radiation Safety R&D

17. Conduct R&D to increase radiation safety for patients and/or workers through radioisotope replacement in therapies and applications.
18. Conduct R&D to improve the radiation safety of radioisotope production and radiation beam facilities (such as automating radiochemistry processes, improving operations or facility design, etc.)
19. Conduct R&D on sealed source and packaging technology.
20. Conduct R&D on radiation health effects, especially low-levels of radiation.

Organizing, Planning and Funding R&D

21. Decouple research and production funding to assure a more stable research funding level.
22. Lead and be a focal point for isotope and radiation technology.
23. Support a balanced R&D portfolio with segments for medicine, industry, agriculture, life sciences, environmental, etc.
24. Increase the involvement of university research reactors in R&D.
25. Develop a new generation of isotopes and radiation experts.
26. Create and facilitate a production Users Group composed of isotope researchers and users (such as NIH researchers, pharmaceutical manufacturers, etc.)
27. Create analogs to the Advanced Nuclear Medicine Initiative program in the areas of industrial and other applications.

28. Provide direct, peer-reviewed grants to researchers, with awards based solely on merit. Create grants for researchers to use DOE facilities.
29. Sponsor and conduct an ANS Topical meeting on isotopes and radiation R&D.
30. Convene brainstorming sessions with non-industry participants on innovative uses of isotopes and radiation.

Objective 2 B Production and Inventory

Production

1. Produce needed isotope “orphans” on a long-term basis. The term, “orphans” refers to isotopes that will probably never become commercially viable, yet have beneficial application.
2. Outsource production to university research reactors whenever possible.
3. Conduct an integrated comprehensive assessment of current isotope production systems. View the national laboratory, university and commercial sectors as an integrated production system.
4. Build new, dedicated isotope production capability.
5. Upgrade or modify existing facilities to meet changing demands.
6. Establish key partnerships with producers of isotopes.
7. Identify and evaluate key facilities for use by researchers.
8. Evaluate a policy to achieve domestic self-sufficiency for selected isotopes.
9. Establish or maintain effective regional production and distribution of short-lived radioisotopes.
10. Study production facility reliability, and establish programs to improve reliability.
11. Establish an appropriately sized, flexible facility for producing enriched isotopes (specifically including radioactive).
12. Maintain and enhance isotope production and radiation source infrastructures.

13. Coordinate international sources of isotopes for domestic needs.

Marketing and Distribution

14. Provide low-cost (or at least below-cost) isotopes to researchers.
15. Establish a single point-of-contact for isotope and radiation source availability.
16. Establish good business practices customized for individual customer groups.
17. Create and facilitate an Advisory Group composed of isotope researchers.
18. Develop a realistic cost/pricing method for production of isotopes and use of facilities.
19. Study and update yearly demand forecasts for isotopes, and review production goals.

Standards

20. Support participation in the development of national standards (such as ANSI or US Pharmacopeia standards for purity, use, disposal, etc.)
21. Produce unique physical standards not provided by NIST.
22. Act to assure the traceability of DOE-produced standards to NIST.

Inventories

23. Preserve and maintain potentially useful isotope inventories (both stable and radioactive).
24. Catalog and publicize production and inventory of isotopes and sources, as well as facilities and staff, for existing and potential users.
25. Guarantee the availability and reliability of isotopes.

Objective 3: Fostering Applications

1. Encourage collaborative efforts with industry that can afford improvements in commercial technology (such as CRADAs or sponsored research).
2. Study the transportation, regulatory issues and technology associated with isotope delivery.
3. Establish a demonstration facility for pilot applications of isotope-based applications (such as waste treatment, processing, etc.)
4. Sponsor public advertisements.
5. Supply isotopes at no cost for demonstration of new, proposed uses.
6. Provide technical support for new, innovative isotope and radiation applications.
7. Create and encourage User Groups for isotopes, and sponsor workshops, seminars, etc.
8. Establish a clear policy statement on isotopes and radiation, to the effect that they have a great benefit and that DOE will foster their use.
9. Facilitate and fund university, national laboratory and commercial collaboration to use isotopes and radiation sources.
10. Make an annual award to recognize important and innovative research and applications of isotopes and radiation sources.
11. Develop a systematic method for evaluation, and perform cost/benefit analyses to guide isotope deployment decisions.
12. Provide leadership and seek to enhance collaboration with other government agencies.
13. Monitor commercial, government and university sectors for potential improvements and brainstorm new applications of isotopes and radiation sources.

14. Sponsor high-visibility experiments on the International Space Station.
15. Sponsor an annual conference on the uses of isotopes and radiation.
16. Establish regulatory assistance for potential users.
17. Lower the barriers for first-time users.

Objective 4 B Education

1. Continue to provide information on the beneficial uses of isotopes and radiation.
2. Publicize R&D needs for isotopes and radiation.
3. Provide educational seminars to Congressional members and staff.
4. Organize and fund specialized workshops and visits to DOE facilities for potential researchers and users, including students.
5. Establish national laboratory and university staff sabbaticals, etc.
6. Sponsor summer programs for students at the national laboratories
7. Create an ANS Student Design Competition on isotopes and radiation sources and applications.
8. Sponsor a funded chair for Isotopes and Radiation at a university.
9. Establish a Speaker's Bureau to reach the public, potential users and universities.
10. Establish short courses and workshops for industry.
11. Write a paper for *MIT Technology Review* (or other magazines) on the use of isotopes.

Medical and Industrial Isotope Applications Working Group

Linkages to Other Plans

DOE Strategic Plan: Sciences and Technology

Strategic Goal: Deliver the scientific understanding and technological innovations that are critical to the success of DOE's mission and the Nation's science base.

Objective: Deliver leading-edge technologies that are critical to the DOE Mission and the Nation.

Strategy: Develop the technologies required to meet DOE's energy, national security, and environmental quality goals

Supply quality, stable, and radioactive isotopes for industrial, research and medical applications that continues to meet customers specifications and maintain 95% on-time deliveries in FY 1998 and beyond.

DOE/NE Vision: Benefits of nuclear technology to our society can and should be expanded.

R&D Objective: Conduct medical research to broaden and improve the application, type, and effectiveness of nuclear medical therapies.

Objective: Interact with foreign researchers and promote cooperative R&D programs with foreign governments in order to share the cost and expand expertise.

Provide assistance to college nuclear engineering programs to foster academic excellence and improve nuclear research and training facilities.

Appendix C

Working Group Report on – Materials and Corrosion R&D

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Materials And Corrosion Research Needs Working Group
October 18-20, 1999 Workshop

C:\wpdata\NERAC10.M&C.doc 1.19.2000

DOE LONG-TERM NUCLEAR ENERGY R&D PLAN
MATERIALS AND CORROSION RESEARCH NEEDS

INTRODUCTION

Safer, more environmentally benign, longer operating, better performing and economically superior nuclear fission power reactors and radioactive waste containment systems, and more generally optimization of the entire nuclear fuel cycle, will require improvements in materials and corrosion prevention. The design and nature of the next generation nuclear power systems are still unknown. Thus, the materials and operating requirements (temperature, coolant, etc.) are not well defined. It is eminently clear, however, that improved radiation and corrosion resistance will be needed. Similar unknowns exist for the nuclear fuel cycle; for example, will spent nuclear fuel continue to be considered a preferred waste form or will alternative concepts, such as accelerated transmutation of waste (ATW) be implemented. Since new science or new materials often take as long as 20 years to be implemented into new technology, it is imperative that long-term research and development on improved materials, materials performance, and corrosion be undertaken in advance of new designs.

The materials science paradigm, in which synthesis and processing is used to manipulate materials' microstructures in order to improve properties, offers tremendous potential for stimulating innovation and driving progress in many areas of nuclear technology. In their report to the President dated November, 1997, and entitled "Federal Energy Research and Development for the Challenges of the Twenty-First Century", the President's Committee of Advisors on Science and Technology (PCAST) stated "The Federal Government's role is to ensure that long-term problems with nuclear power are addressed so that nuclear can become, if possible, a realistic and acceptable energy option, as well as a hedge in case renewables and efficiency cannot reach the performance levels and market share necessary to meet emission reduction targets." The long-term materials and corrosion research needs described below were formulated to meet the stated goal.

We have divided this report into sections that correspond to various long-term research topics in materials and corrosion. This classification does not imply that borders actually exist between these topics. Any research project that addresses long-term needs and opportunities for improved materials and corrosion prevention may indeed cut across any number of the topics that are identified below, and many of them are interrelated. As the following sections describe in greater detail, cutting-edge materials science and engineering research is a critical need in each of these topics, and there is substantial opportunity for consequential technological pay-off and scientific excitement in all of them.

IRRADIATION ASSISTED STRESS CORROSION CRACKING AND AQUEOUS CORROSION

There is insufficient fundamental understanding of radiation effects on alloy behavior at LWR temperatures and dose-rates to reliably predict component properties and thus mitigate service failures. A recent assessment of the radiation-induced material changes that are believed to influence LWR core component cracking is available [1]. This report also identified long-term research needed to elucidate the underlying failure mechanisms. Our discussion on this topic largely follows from that review.

A growing concern for electric power utilities worldwide has been the degradation of core components in nuclear power reactors, which currently generate ~17% of the world's electric power. Failures have occurred after many years of service in boiling water reactor (BWR) core components and, to a lesser extent, in pressurized water reactor (PWR) components. These failures occurred in stainless iron- and nickel-base alloys exposed to sufficiently high levels of neutron irradiation in the reactor coolant environment. This environment is typically oxygenated or hydrogenated water at about $290^{O}C$, but the temperature can range from $270^{O}C$ to $370^{O}C$ in specific locations. The coolant chemistries can become more aggressive in crevice situations, where component failures are often observed. Since cracking susceptibility requires a combination of radiation, stress and a corrosive environment, the failure mechanism has been termed irradiation assisted stress corrosion cracking (IASCC). Until recently, the components affected have been either relatively small (bolts, springs, etc.) or designed for replacement (control blades, instrumentation, tubes, etc.), but more structurally significant components such as top guides and core shrouds have also been degraded. Because testing of irradiated materials is difficult and expensive, it is highly unlikely that a purely empirical approach will provide an adequate understanding of IASCC behavior.

Recent reviews [2 - 7] have been published which describe much of the current knowledge related to IASCC service experience and laboratory investigations. These reviews highlight the limited amount of controlled experimentation that exists on well characterized materials. Moreover, there are inherent difficulties in quantifying SCC response that preclude direct comparisons between radiation-induced changes and cracking behavior. This lack of critical experimentation underscores the necessity that a scientific approach be pursued to acquire a fundamental mechanistic understanding of IASCC.

Advances in IASCC understanding require research focused in radiation materials science, and more generally, on the fundamentals of grain boundary behavior, corrosion, localized deformation and fracture. Radiation materials science begins with the atomic displacement processes that drive microstructural changes. However, linking these changes to environmental cracking requires that underlying principles be elucidated for both irradiated and unirradiated conditions. A detailed discussion of the research needed to improve the mechanistic understanding of radiation-induced material changes and IASCC of LWR core components is presented in [1]. This underpinning knowledge is essential for the continued effective operation of current LWRs and for the design of optimized nuclear power systems.

Important progress has been made over the last decade to identify specific parameters that promote IASCC susceptibility. It is now clear that persistent radiation-induced changes control the behavior. Application of high-resolution characterization techniques to IASCC in LWR-irradiated materials has clarified many issues related to microstructural and microchemical evolution during irradiation.

However, nearly all measurements have been performed on uncontrolled commercial stainless steel heats without any systematic variation of irradiation or material parameters, especially composition.

Hence, there is a paramount need for mechanistically driven, single-variable experiments to elucidate radiation-induced material changes and their effects on IASCC. The use of alloy compositions and irradiation conditions much broader in scope than the standard LWR component experience is crucial to understanding IASCC behavior and uncovering opportunities for improved materials. Optimal compositions and conditions must be selected based on a fundamental understanding of radiation-induced changes. Prior experience [8,9] in establishing the mechanisms and material variables controlling void swelling and in the development of swelling-resistant materials provides excellent examples of how advances in fundamental understanding can lead to important practical advances.

Reference [1] identifies and elaborates on the following research needs in radiation materials science: (1) defect production and clustering in multi-component materials, (2) multi-scale microstructural modeling , (3) transient evolution of microstructure, and (4) defect/solute interactions at grain boundaries. The microstructural defects that form and the changes in grain boundary composition that occur are now qualitatively well understood. However, accurate prediction of microstructures, microchemistries and mechanical property changes in complex stainless alloys during irradiation at LWR temperatures is not currently possible. Mechanistic understanding of these radiation-induced changes in commercial alloys is of paramount importance to predict and mitigate intragranular cracking that occurs in service. The proposed research is needed to define microstructural and microchemical evolution at intermediate temperatures and dose rates pertinent to LWRs where transient effects often dominate.

It must, however, be recognized that advances in radiation materials science alone are not expected to produce a mechanistic understanding of IASCC. The radiation-induced material changes must be linked to known (and perhaps yet unknown) structure-property relationships. A continuum must exist between the behavior (e.g., grain boundary properties, corrosion reactions, deformation and fracture) of unirradiated materials and that under irradiation. The continuum approach recognizes that the irradiated alloy properties are not unique. The role of irradiation is simply to perturb the microstructure and microchemistry, and thus to change the threshold for intragranular cracking. The crystal structure, base alloy composition and exposure to stress are the same for irradiated and unirradiated alloys, although critical details in the material's condition differ. A consistent interpretation of material response must be developed that satisfies our mechanistic understanding of both irradiated and non-irradiated behavior.

Thus in addition to the research in radiation materials science described above, additional areas needed to understand IASCC include: (1) deformation and fracture, (2) grain boundary structure and properties, and (3) corrosion/electrochemistry in high-temperature water environments, including properties of the material/environment/oxide interface at the crack tip. Radiation impacts each of these areas, but the underlying mechanisms are common to irradiated and non-irradiated materials.

In addition to the corrosion issues directly linked with irradiation, related long-term research needs also exist in general corrosion phenomena including crevice corrosion and high temperature aqueous chemistry. Needs for improved understanding in corrosion include, but are not limited to, problems involving compatibility with water at relevant elevated temperatures, and stress-corrosion cracking (SCC) in general. A better understanding of the processes underlying SCC should permit the development and use of less expensive SCC resistant materials than those now in use, and may also reduce the dependence on expensive testing programs.

Crevice corrosion involves aggressive chemical environments in a localized region. It can occur both on macroscopic, e.g., in the region between a steam generator tube and the tube support plate, and on microscopic levels. Modeling and experimental research, including the development of instrumentation to measure the chemical environment within a crevice, would permit evaluation of critical parameters such as corrosion, and crack propagation rates, and help identify mitigative measures such as changes in environment, again reducing the dependence on difficult and expensive testing. Corrosion processes depend on the chemical reactions that occur between the environment and the materials of interest. Such chemical processes, including the formation of insoluble precipitate films, also play an important role in the development of crevice environments. Characterization of these reactions is critical for the development of predictive models for corrosion related-phenomena.

References:

1. S. M. Bruemmer, E. P. Simonen, P. M. Scott, P. L. Andresen, G. S. Was and J. L. Nelson, Radiation-induced Material Changes and Susceptibility to Intergranular Failure of Light-water-reactor Core Internals, J. Nucl. Mater. 274 (1999) 299-314.

2. P. Scott, J. Nucl. Mater. 211 (1994) 101.

3. P. L. Andresen, in: R. H. Jones (Ed.), Stress Corrosion Cracking, ASM International, Metals Park, OH, 1992, p. 183.

4. P. L. Andresen, F. P. Ford, S. M. Murphy and J. M. Perks, in: D. Cubicciotti and G. J. Theus (Eds.), Proceedings of the Fourth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems -- Water Reactors, National Association of Corrosion Engineers, 1990, p. 1.

5. J. L. Nelson and P. L. Andresen, in: Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems --Water Reactors, American Nuclear Society, La Grange Park, IL, 1992, p. 10.

6. G. S. Was, P. L. Andresen, J. Met. 44-4 (1992) 8.

7. G. S. Was, S. M. Bruemmer, J. Nucl. Mater. 216 (1994) 326.

8. L. K. Mansur, "Theory and Experimental Background on Dimensional Changes in Irradiated Alloys", J. Nucl. Mater. 216 (1994) 97-123.

9. F. A. Garner, in: B. R. T. Frost (Ed.), Chapter 6 of Nuclear Materials, Part 1, VCH Verlagsgesellschaft, Weinheim, Germany. Materials Science Forum, vol. 10.

REACTOR PRESSURE VESSEL EMBRITTLEMENT

The Department of Energy's Office of Nuclear Energy and Office of Basic Energy Sciences/Materials Sciences, along with the Nuclear Regulatory Commission and the Electric Power Research Institute jointly sponsored a Research Assistance Task Force (RATF) on reactor pressure vessel embrittlement which took place on 20 - 21 September 1999. The proceedings of this meeting have been published [1] in the form of a report that contains summaries of the deliberations of the meeting, along with the presentation materials of all the speakers. Below we summarize the findings and recommendations of this meeting.

Reactor pressure vessels (RPVs) are massive ferritic steel structures. In these materials there is a well known ductile-to-brittle transition temperature (DBTT). Above the DBTT the material fails in a ductile manner, and the fracture toughness is high. Below the DBTT the energy to cause fracture is low and failure is characterized as brittle based on fractographic characteristics. Irradiation causes the DBTT to shift upward, while simultaneously decreasing the upper shelf energy, i.e., the fracture toughness at temperatures above the DBTT. This area comprises a large field that spans materials science research and materials engineering in the support of light water reactor technology. In steels not tailored to be radiation resistant, the DBTT can reach hundreds of degrees C and the lowering of the upper shelf energy can be tens of percent, even at doses well below the end of life displacement damage level of ~0.01 dpa for RPVs. Of main concern is the possibility that with such large shifts, brittle behavior could be encountered near the temperature regime of normal reactor operation or shutdown. In addition to improving the material's behavior in response to this concern, a more precise knowledge of the in-service toughness of the RPV would have a substantial positive impact on the operation of existing power reactors. In particular, more precise knowledge can be expected to save in excess of $4 M per reactor by permitting less conservatism in cool-down and start-up procedures [2].

Materials research on the effects of impurities and alloying elements such as copper, nickel and phosphorous has resulted in substantial improvements in the performance of ferritic pressure vessel steels. By controlling alloying elements, the DBTT shift can be reduced several fold. However, the physical processes underlying these elemental effects are not understood on a mechanistic microstructural basis. Further improvements in performance beyond the considerable advances already achieved by traditional empirical metallurgical approaches will require advances in materials science research.

The needs for this research are: (1) to improve the economics and safety of operating reactors by reducing unnecessary conservatism in current reactor start-up and shut-down procedures. (2) to improve understanding of the connections between defects, microstructure and macroscopic mechanical properties, in order to formulate predictive models. (3) to obtain maximum benefit from current embrittlement surveillance programs. Although enormous amounts of data have been accumulated under actual operating conditions in numerous reactors on various steels in myriad conditions, without the purposeful control of variables that characterizes the materials science approach, it is difficult to obtain insight from these data into the basic mechanisms of embrittlement, and empirical correlations based upon such data inherently contain large uncertainties.

Testing of surveillance specimens does not address certain important issues, including:
(1) the substantial effect of flux attenuation through the vessel thickness. (2) the spatial variability of microstructure and properties over such large structures, (3) the validity of embrittlement correlations

and (4) characterization and behavioral effects of processing-induced banding and segregation. To address these issues requires obtaining and testing materials from decommissioned pressure vessels.

Similarly, there is a critical need to retain and preserve surveillance specimens. Even though the retention of irradiated but untested materials may no longer be required by regulations, these specimens are irreplaceable in terms of the time and operating conditions to which they have been exposed. It is also necessary to account for the fact that the irradiated material in a given surveillance specimen is generally not of precisely the same microstructure, chemical composition or defect state as nominally the same material at an arbitrary location within the massive pressure vessel structure.

The effects of very long irradiation times, i.e. $>10^5$ hours, require experiments and modeling that embrace (1) gathering and analysis of further statistical evidence for recent preliminary reports of increased embrittlement rates at long times. (2) assessment of the importance of long irradiation time-induced embrittlement, in view of possible extensions of reactor lifetimes to 60 or even 80 years. (3) development of reliable predictive models for behavior, based on understanding the mechanisms that are responsible for microstructural development, including the possible formation of late-blooming phases, and (4) understanding the interplay between long term thermal aging phenomena and long term radiation effects.

The mechanistic basis for mechanical behavior that led to the empirical success of the "master curve" approach needs to be better understood. The shift in fracture toughness transition temperature needs to be reliably modeled in a physically based approach that is rooted in microstructure and precipitate evolution. Thorough experimental characterization of the transition in fracture toughness is necessary over a wider range of materials and conditions. This includes the resolution of technical issues that are associated with the application of the master curve approach.

There is a strong need for detailed knowledge of the structure and composition of both the matrix defects and copper-containing precipitates that underlie embrittlement. The matter is complicated by the fact that there generally exists a wide range of precipitates and clusters, some of which are only loose correlations of atoms that do not fit the description of precipitates in the usual metallurgical sense. Knowledge of the degree of co-segregation of additional solutes, e.g., P, Mn, Ni, and Si, to these extended defects, as well as knowledge of their interactions with mobile dislocation segments, are also required before improved predictive models of irradiation-induced mechanical property changes can be constructed.

Molecular dynamics simulations of cascade production, as well as other atomic level calculations, which provide information over atomic distances and unprecedented small time scales (0 to 100 ps), currently suffer from inadequate interatomic potentials. Such potentials need to be developed. The integration of multi-scale approaches on theoretical and experimental levels needs further development. The modeling methodologies range from molecular dynamics simulations at the atomic scale to global defect reaction rate theory for predicting the evolution of microstructure and precipitation and the concomitant effects on properties [3]. The situation with embrittlement is more involved than with similar work on radiation-induced dimensional changes. In work on radiation induced swelling and creep, for example, the output of microstructure and precipitation predictions emerging from these methods is sufficient in principle to determine completely the swelling and creep behavior. However, for radiation induced embrittlement, the microstructural state, whose quantification by calculation is very demanding and presently achieved only in special cases, is merely a first phase in the determination of embrittlement. Once the microstructural state of the material has been reproduced by this type of modeling, further continuum dynamics methods need to be integrated for predicting deformation and fracture behavior of the material in its evolved microstructural state. In the development of such integrated multi-scale models, it is always crucial to "benchmark" computations and simulations against experimental measurements.

Some of the expectations for success of long term research on issues related to reactor pressure vessel embrittlement are: (1) further reductions in the ductile-to-brittle transition temperature at high neutron fluences, (2) reduction in excessive conservatism in reactor design and operating rules, and (3) understanding of the mechanisms of response of pressure vessel materials during annealing and re-embrittlement. In turn this will permit more reliable knowledge of vessel condition and more efficient reactor operation.

References:

[1] L. K. Mansur, editor, Proceedings of the Research Assistance Task Force on Radiation Materials Science Applied to Reactor Pressure Vessel Embrittlement, September 20-22, 1999, Charleston, SC, Oak Ridge National Laboratory Report M99-105308

[2] Electric Power Research Institute Report TR111142.

[3] L. K. Mansur, "Mechanisms and Kinetics of Radiation Effects in Metals and Alloys," in *Kinetics of Nonhomogeneous Processes*, G. R. Freeman, Editor, John Wiley and Sons, 1987, pp. 377-463.

MECHANISMS AND MODELING FOR THE DEGRADATION OF RADIOACTIVE WASTE PACKAGES

The nuclear waste package for interim storage or permanent disposal currently consists of spent nuclear fuel assemblies or other solid nuclear waste forms contained in metal canisters. The properties of the spent nuclear fuel, other solid nuclear waste forms, and the canister itself, may degrade in the presence of water or radiation damage from radionuclide decay [1,2,3]. The degradation processes due to corrosion and radiation damage must be understood well enough that extrapolations of waste package behavior can be made confidently over periods of at least ten thousand years. Public acceptance of nuclear power as an important energy source depends on developing acceptable solutions to the backend of the nuclear fuel cycle; scientifically-based and carefully engineered solutions are more likely to gain public acceptance. Other countries pursue strong research programs on all phases of the commercial nuclear fuel cycle, particularly materials science issues related to the reprocessing of spent nuclear fuel and development of waste forms and packages. Hence opportunities for international collaboration, and mutual benefit exist.

Spent nuclear fuel (SNF), which contains over 95% of the total radioactivity that requires geologic disposal, is the principal waste form in the United States. It is essentially restructured UO_2 with approximately 4 percent fission products and transuranium elements, such as Pu and Am. Although there has been considerable research on radiation effects in highly crystalline UO_2 and UO_2 fuel under reactor irradiation [2], the effects of self-radiation at ambient temperatures in restructured, highly-damaged UO_2 that may not be stoichiometric are not known. While UO_2 is highly radiation stable, the higher uranium oxide, U_3O_8, is one of the easiest materials to amorphize [4] under irradiation. Since very little is known about radiation effects in nonstoichiometric UO_2, there is need for research in this area. There is also still considerable work required to elucidate the corrosion processes and products of UO_2 for scenarios invoking canister failure. Under oxidizing conditions, such as will exist at Yucca Mountain, the corrosion products of UO_2 [5,6,7], mainly U(VI) hydrated phases, will form rather quickly (on a scale of hundreds of years once exposed to water vapor) and may become the principal host phases for transuranium elements and some of the fission products of concern (e.g., Se [8] and Tc [9]) . These U(VI) hydrated phases could therefore become the dominant source of actinides and other radionuclides released to the environment. The oxidative-corrosion process of this semiconductor material is also accelerated due to surface-dominated reactions with free radicals that result from radiolysis of water in contact with the fuel.

The metal containers that make up the waste package were originally proposed to consist of thick layers of corrosion resistant metals and were estimated to cost approximately $300,000 each. More complex designs (e.g., double layers) or exotic alloys are now under consideration to improve the corrosion resistance of the canisters, but the cost estimate per canister is greatly increased (approaching $1 million each). The large volume of current commercial spent nuclear fuel assemblies in the USA (approximately 35,000 metric tons) will require on the order of 10,000 such containers for a net cost estimate of up to $10 billion. An improved scientific understanding of the actual mechanisms and kinetics of degradation for canisters, SNF, new fuels and cladding, and other solid waste forms over geologic time periods would significantly reduce the large uncertainties in performance assessments, thereby reducing costs and risk to the public.

Storage concepts involving the partitioning of radionuclides into more durable waste forms, or into inert matrices for transmutation using accelerator-based neutron sources or nuclear reactors, appear promising. Recent studies [10, 11] suggest that actinides can be incorporated into radiation-resistant ceramics that demonstrate outstanding resistance to environmental degradation. While such results are encouraging, validation of these concepts and materials will require vigorous experimental programs and the sort of computer modeling described later in this report. Similarly, any decrease in the volume of spent nuclear fuel through transmutation, such as through the ATW (accelerator transmutation of wastes), will reduce the direct cost of disposal proportionately.

Internationally and in the USA there is a considerable focus on the fate of weapons Pu (approximately 100 metric tons); however, larger amounts of Pu are generated by commercial power production (approximately 70 metric tons per year world-wide). The present world inventory of Pu is greater than 1,300 metric tons, and the amount of separated Pu from reprocessing commercially generated spent nuclear fuel (outside the USA) is approximately equal to the amount of weapons grade Pu produced for the various national defense programs. As already noted, the partitioning of the actinides for immobilization or transmutation offers promising alternatives to the direct disposal of SNF. Greater involvement of USA scientists and expertise in the development of acceptable solutions to this international issue could increase public acceptance of the nuclear power option in the USA. A significant amount of scientific understanding is needed, particularly related to radiation effects and corrosion, on actinide-bearing solids that may be used as inert matrix fuels or eventual waste forms, as is being considered in Europe. Highly durable, radiation-resistant waste forms for actinides are desirable [10] and potentially attainable [11].

In the future, if the partitioning of radionuclides becomes part of a new nuclear fuel cycle, then highly durable and radiation-resistant materials can be utilized for immobilization of radionuclides, whether for disposal or transmutation. Under such circumstances, the waste forms or transmutation hosts themselves could be the primary containment systems for final deposition, limiting the need for expensive waste package containers. Research and development of new materials and reliable performance models need to be initiated far in advance of when they will be needed. Clearly, significant improvements in safety, reliability, and public acceptance of nuclear technology can be realized through the development and study of new materials and concepts.

References:

1. W. J. Weber, R. C. Ewing, C. A. Angell, G. W. Arnold, A. N. Cormack, J. M. Delaye, D. L. Griscom, L. W. Hobbs, A. Navrotsky, D. L. Price, A. M. Stoneham, and M. C. Weinberg, Radiation Effects in Glasses Used for Immobilization of High-Level Waste and Plutonium Disposition, J. Materials Research, 12 [8]: 1946-1978 (1997).

2. W. J. Weber, R. C. Ewing, C. R. A. Catlow, T. Diaz de la Rubia, L. W. Hobbs, C. Kinoshita, Hj. Matzke, A. T. Motta, M. Nastasi, E. K. H. Salje, E. R. Vance, and S. J. Zinkle, Radiation Effects in Crystalline Ceramics for the Immobilization of High-Level Nuclear Waste and Plutonium, J. Materials Research, 13{6}: 1434-1484 (1998)

3. R. C. Ewing (1999) Less Geology in the Geological Disposal of Nuclear Waste, Science, 286, 415-417.

4. Hj. Matzke and J. L. Whitton (1996) Ion Bombardment-Induced Radiation Damage in Some Ceramics and Ionic Crystals, Canadian Journal of Physics, 44, 995-1010.

5. R. J. Finch and R. C. Ewing (1992) Corrosion of Uranite Under Oxidizing Conditions, Journal of Nuclear Materials, 190, 133 - 156.

6. P. C. Burns, R. C. Ewing, and M. L. Miller (1997) Incorporation Mechanisms of Actinide Elements into the Structures of U^{6+} Phases Formed During the Oxidation of Spent Nuclear Fuel, Journal of Nuclear Materials, 245, 1-9.

7. F. Chen, R. C. Ewing, and S. B. Clark (1999) The Gibbs Free Energies and Enthalpies of Formation of Uranium (VI) phases: An Empirical Method of Prediction. American Mineralogist, 84(4), 650-654.

8. F. Chen, P. C. Burns, and R. C. Ewing (1999) ^{79}Se: Geochemical and Crystallo-chemical retardation mechanisms. Journal of Nuclear Materials, 275, 81-94.

9. F. Chen, P. C. Burns, and R. C. Ewing (in press) Near-field Behavior of ^{99}Tc During the Oxidative Alteration of Spent Nuclear Fuel. Journal of Nuclear Materials.

10. R. C. Ewing (1999) Nuclear Waste Forms for Actinides. Proceedings of the National Academy of Sciences, 96(7) 3432-3439.

11. S. X. Wang, B. D. Begg, L. M. Wang, R. C. Ewing, W. J. Weber and K. V. Govidan Kutty (1999) Radiation Stability of Gadolinium Titanate: A Waste Form for Plutonium Disposition, Journal of Materials Research, 14[12], 4470-4473.

WELDING AND JOINING

Reliable welding and joining procedures are necessary for joining metals, ceramics, and dissimilar materials in general. This need pertains both to the construction of future reactor systems and for the on-line repair or refurbishment of aging existing ones.
Particular concerns include the welding repair of irradiated steels and corrosion resistant alloys, development of crack resistant filler metals for nickel based alloys and reliable joining of ceramic composites. Advancing new welding processes and developing new welding procedures can help prevent expensive power outages attributed to weld-related problems. Some of the recent areas for welding research in the nuclear power industry were highlighted in the EPRI (Electric Power Research Institute) Journal [1]. The following paragraphs are largely based on quotations from this article.

Weld failures are unavoidable and are a common cause of down time in fossil and nuclear energy plants. Day in and day out, metal parts are exposed to cycles of extreme temperatures and pressures, radiation, corrosion, and other factors that take their toll in the form of cracks, splits, ruptures, embrittlement, and pitting. As the U. S. power industry nurses its aging facilities where more than half of its nuclear plants are over 15 years old, welding is going to become an even hotter topic. Better welds can extend the lifetime of older components by decades and can save the industry billions of dollars. A good weld extends plant life, enhances safety and reliability, and cuts down on operation and maintenance costs. These benefits are especially important in nuclear plants, where a day of forced outage costs $300,000 to $750,000.

New welding technologies such as laser welding, underwater welding and temperbead repair welding make possible the ability to weld parts on-site, and sometimes in-situ, which greatly reduce the cost of weld repairs. In today's competitive business environment, in which it may be cheaper to maintain an old plant than build a new one, welding is a crucial aspect of plant management. It represents 10% of new construction costs and 20% of maintenance costs. In some cases welding may provide the only economically viable approach for avoiding a permanent plant shutdown.

Temperbead repair

Temperbead repair can be considered the innovation that has made the biggest impact on the industry. Many of the steels used for piping and pressure vessels must be given post-weld heat treatments (PWHT). This treatment softens or tempers the hardened material after a weld is performed and so relieves residual stress. It also allows the diffusion of hydrogen, which is introduced into the metal during welding and can cause cracking. But PWHT is time-consuming and expensive, especially when the components involved are large or when many treatments are necessary. In nuclear plants, it can take up to 12 hours for a component to reach the desired temperature, 1 to 3 hours to perform the treatment, and another 8 to 12 hours for cooling. Sometimes PWHT may not even be possible because of the size or configuration of the flawed part.

Temperbead welding performs the same function as conventional arc welding with PWHT, and its results can be equal or superior. In this process, welding beads are deposited in precisely controlled patterns, and each successive bead provides heat tempering for the layer directly below it. It is an especially valuable technique for the in-situ repair of large components, including pressure vessels and turbine casings, which have traditionally needed to be removed for repair off-site. Carbon steels and low-alloy steels can now be repaired without PWHT as long as the repair produces toughness properties comparable to those of the base metal.

Although major improvements have been made in temperbead repair welding over the past few years, more research and development is needed to extend, if possible, this technique to encompass higher chromium content steels such as the P91 materials. These materials are being used for new construction around the world due to their better strength-to-weight ratios and reduced overall costs. More importantly in the U.S., utilities are using the material for retrofits or replacement of aged piping or tubing. Temperbead technologies to allow utilities to replace piping/tubing would result in huge savings in terms of postweld heat treatment costs.

Laser welding

Advances in the field of laser welding have recently made possible the delivery of multi-kilowatts of NdYAG power through sub-millimeter diameter fiber optic laser delivery systems. These high power lasers provide excellent welding sources because of their high power density, their ability to be automated, and their ability to weld in remote locations. Since workers have the option of defocusing the beam over larger areas, lasers can also provide a means to enhance weld and material properties through localized heat treatment. Compared with conventional methods, automated laser welding is faster, requires less finishing and machining, and can repair damaged parts that once were considered hopeless. Other advantages of laser welding may include precision, minimal weld dilution and minimal heat affected zone sizes.

Lasers also have the ability to melt powdered filler metals for localized weld repair, cladding, and surface alloying. The ability to melt special powders allows welders to create complex mixtures appropriate for both the initial application and for the repair of ceramic thermal barrier coatings (TBCs). Structural type repairs of superalloy gas turbine blades are being studied to repair the high-stress regions of blade airfoils, and lasers are being looked at to develop repair alternatives for directionally solidified materials such as GTD-111.

The potential of lasers in power plant applications has only begun to be tapped. Perhaps the largest advantage of laser welding is in providing excellent opportunities for repairing components on site and in situ without having to open up the reactor. Such repairs can potentially avoid the high cost of extended period shutdowns. One of the big challenges for the laser welding industry will be in the development of higher average power laser systems that can be taken to the field. Higher power lasers would enable increased deposition rates for repairs of power plant components such as rotors and piping. Laser cladding, to combat corrosion/erosion of waterwalls and wear of valves, will also benefit from enhanced laser power. In addition to higher laser power, all on-site laser applications will benefit from the development of better techniques for automating laser welding repairs, which will cut welding costs and minimize the chance for human errors.

Underwater welding

In the nuclear power industry, underwater welding has recently been employed in repairing boiling water reactors. Although it is difficult for repair workers to go into a reactor because of radioactivity and access limitations, it is done under certain circumstances. It is safer for workers to perform such work underwater because water itself offers great protection from the radiation. This avoids the need for the extra shielding that is required when a reactor is drained. To avoid the problems associated with repair workers having to enter reactors, much underwater welding is automated. It is mainly used to make repairs inside the lower two-thirds of a reactor pressure vessel, which is inaccessible and radioactive, and to repair fuel storage pools.

Recent examples of core shroud cracking and the potential for degradation in other RPV components highlight the need for the development of specific repair technologies. Underwater welding technology developed for austenitic materials should be expanded to include irradiated materials. Highly irradiated materials (10^{24}n/m^2 or greater) contain a concentration of helium that can lead to underbead cracking and hot tearing of welds and heat affected zones. Empirical evidence suggests that low heat input, low dilution welding processes might provide good results. Several underwater options are available including flux-cored arc, plasma-arc, and laser welding techniques. Research directed towards improving the stability of arcs at water depths below 50 feet is required, and needs exist for developing new welding electrodes with improved wet weld characteristics. There are several needs for the successful development of irradiated welding technology, which include the identification and acquisition of suitable test materials, coordination of underwater facilities with hot labs, welding and testing of equipment, and assessment of "weldable" helium levels.

Reference:

[1] Vis Viswanathan and David Gandy, "Welding Research Heats Up," EPRI Journal, Spring 1999

NON-DESTRUCTIVE EVALUATION AND CONDITION MONITORING

Non-destructive evaluation (NDE) has two very critical functions in the production of nuclear energy. One of these functions is to provide the highest possible quality assurance for the components that comprise a reactor and for periodic inspections during outages. Improvements of this sort include both the detection and characterization of flaws and the characterization of the properties of the material in which they might reside. Regarding discrete flaws, decreasing the flaw size that can be reliably detected, increasing the ability to characterize and size those flaws (e.g. differentiating them from benign geometrical discontinuities, and developing techniques that can detect such flaws in parts of increasingly complex geometry (without the need to modify that geometry for the inspection), are all important issues. Improvements in the speed, accuracy, resolution and detectability limits of such techniques will lead to improvements in plant safety, operating efficiency and the safe lifetime of components. Quality assurance techniques also include the characterization of failure related properties of the material in which the flaws reside. Important targets include techniques to measure embrittlement and remaining fatigue life.

A second function of NDE is to provide continuous condition monitoring, i.e., in-situ or on-line early warning of possible impending or catastrophic component failure, including the ability to predict the remaining safe lifetime for a component. This implies that the sensor both give the requisite information (based on sound measurement principles) and that it be able to survive and function under the hostile environments that are seen by the component itself. Examples include irradiation, high temperatures, stress, and an aggressive or corrosive chemical environment. There are many opportunities here for long term research.

Ultrasonic, electromagnetic (especially eddy current) and radiographic techniques receive by far the most usage in the detection, characterization and sizing of flaws because of their ease of use in the challenging nuclear power plant environment. There are important opportunities for the development of improved signal processing procedures to better discriminate signals from background noise, for artificial intelligence techniques to discriminate between signals from flaws and those from benign geometrical discontinuities, and for inverse scattering techniques for determining the sizes of flaws. As a specific example, improved NDE techniques are needed to characterize flaws in steam generators, where it is very difficult to distinguish between harmful crack-like defects and innocuous inclusions. In order that these techniques provide the form of output most desirable from a life management perspective, it is highly desirable that they be conducted within a probabilistic format so that parameters such as probability of detection can be quantified.

There is considerable work to be done to develop algorithms that will produce probabilistic output. Early indications show that the use of physical models of the inspection process can play an important role in these developments. The detection of discrete flaws is often rendered quite difficult by the complexity of the surrounding geometry. A classical example is in the area of weldments, in which various geometrical complexities, e.g. offset, can produce signals that are difficult to distinguish from those produced by cracks. A less familiar problem is found in steam turbines, 30% of which suffer from stress-corrosion cracking at the blade to rotor attachment areas known as the steeple. NDE techniques are needed to permit inspection of these regions without having to remove the blades. An example of a possible solution would be a tomographic reconstruction using a form of energy sensitive to the corrosion products.

The measurement of failure related material properties is one of the “holy grails” of NDE whose solution would have tremendous impact [1,2]. For example, development of NDE techniques that can measure the degree of embrittlement of reactor pressure vessel steels caused by long time exposure to radiation would be very cost effective for extending the life of existing pressure vessels. Promising new techniques have been suggested by a program sponsored by the Nuclear Regulatory Commission. [3]. In the area of fatigue life prediction, acoustic harmonic generation has shown considerable promise, showing a much stronger correlation with remaining life than measurements based on linear effects such as ultrasonic velocity and attenuation.

An alternate futuristic approach to property determination is the monitoring of appropriately representative test coupons. For example, fatigue damage accumulation in reactor pressure vessel steels might be measured on test coupons by selected area diffraction, which can measure the change in the cell-to-cell angular misorientation within each grain as a function of damage evolution. More comprehensive studies are needed to develop and validate such techniques and to determine how their performance compares to that of the in-situ measurement techniques discussed above.

In the measurement of material properties, there are two distinct kinds of problems. As noted above, a measurement must be made that is related to the property of interest based on solid physical principles, and some promising candidates have been identified. However, more research needs to be done to gain the level of understanding of the measurement-property relationships needed to guide their implementation with high confidence. In addition, it is often the case that there are considerable geometrical challenges. An example is the fact that embrittlement needs to be sensed in pressure vessel steels that are covered by a stainless steel cladding. Research directed at overcoming these challenges is needed.

It is important that there be a strong coupling between research in NDE and materials science. Mechanisms of degradation must have been identified and understood before acceptable tests can be developed. For example, improved understanding of pitting mechanisms and SCC crack growth phenomena are needed to predict the life of steam generators to avoid enormous costs associated with downtime. It is also important to recognize that new materials and material modification approaches are constantly being developed to improve corrosion and radiation resistance, and it is important that appropriate NDE approaches be developed hand-in-hand with these materials efforts. For example, surface modification procedures are used to either increase resistance to corrosive environments or to enhance specific mechanical properties of materials. Such procedures utilize a variety of methods ranging from relatively simple electrochemical approaches to ion implantation and laser irradiation techniques. Electrochemical deposition methods are also being looked at for repairing leaks in steam generator tubes. New generation nuclear power plants would most likely use a large number of surface modified components, and the development of inspection techniques tailored to their unique problems will be needed. These developments may involve some particularly challenging physical problems, since the dimensional scales of a few microns are in the transition region between mesoscopic and macroscopic dynamics.

It has been noted previously that it is highly desirable that measurement output be given in a probabilistic format. This is important in order for the measurement results to be readily utilized in systems analysis procedures such as probabilistic risk assessment and strategies such as defense in depth.

In future reactor systems, there will be an increased opportunity for condition monitoring (the continuous monitoring of flaws and or material properties) [4]. An important research direction is the development of the appropriate sensors, based on solid physical principles, that can survive when continuously exposed to the reactor environment. The development of new smart materials with the ability to provide in-situ on-line monitoring of material characteristics such as remaining cyclic stress fatigue life, velocity of crack growth, or time to reach critical crack length would increase safety, reduce conservative factors of safety, and provide consequential increases in plant operating efficiency. Ideally, outages could be scheduled based on the true condition of materials rather than a preset time schedule. An attractive feature would be the development of wireless communication procedures to allow the information to be transmitted to a remote site.

Although not part of the reactor per se, the high-level waste processing and storage issue should not be neglected. Research addressing the questions of NDE monitoring of the processing procedures and assuring the integrity of the containment vessels is needed.

There are a large range of emerging research tools that should be explored in the context of the above problems. Broad areas that might provide a basis for major advancements in NDE and condition monitoring may include, but are not necessarily limited to, advanced physical acoustics, positron annihilation, high intensity X-rays, superconducting quantum interference devices (SQUIDs), and artificial intelligence.

References:

1. Nondestructive Characterization of Aging Energy Systems, Journal of Nondestructive Evaluation, Vol. 15, No.3-4, pp. 83-176, O. Buck, T. Taylor, and G. A. Alers, Eds., 1996.

2. Nondestructive Characterization of Material in Aging Systems, R. L. Crane, J. D. Achenbach, S. P. Shah. T. E. Matikas, P. T. Khuri-Yakub, and R. S. Gilmore, Eds. Symposium Proceedings 505 (Materials Research Society, Warrendale Pennsylvania, 1998).

3. Technical Note 1500-4, National Institute of Standards and Technology, Boulder, Colorado, June, 1998 (full report in press).

4. Nondestructive Evaluation of Utilities and Pipelines III, SPIE Conference Proceedings 3588, Walter Reuter, Editor (March 4, 1999)

MATERIALS ISSUES IN ACCELERATOR TRANSMUTATION OF WASTE (ATW) TECHNOLOGY

In ATW technology, as in other complex nuclear systems, the resolution of crucial materials issues will determine the success of the technology. In this concept , the target/blanket assembly (also known as the transmuter module), serves as the target for a high power proton accelerator operating at GeV energy. See, for example, references [1] and [2]. In this module, a heavy metal such as a liquid lead-bismuth eutectic (LBE), or solid tungsten serves as the spallation neutron source, wherein several tens of neutrons are produced per impinging proton. Immersed in and surrounding this target are the fuel elements of a sub-critical assembly, which contains transuranium elements, such as the actinide plutonium, and rods containing long-lived fission products, both of which are produced in the cores of LWRs. The actinides are destroyed by fission reactions, while the fission products are rendered stable or transmuted to short-lived radioactive products by neutron absorption reactions. In these processes, heat is produced, which may be harnessed for the production of electricity.

Issues requiring advances in materials science and engineering are numerous in the design, fabrication and performance of the target/blanket module. Other important materials issues must be addressed in the separation and fabrication processes entailed in producing and disposing the actinide- and fission product-containing host forms. The issues for the target/module design, fabrication and performance are in some cases similar to those already addressed in the work already underway for the Spallation Neutron Source at Oak Ridge, and other high power spallation neutron sources in design in Europe and Japan. In these spallation neutron sources, the spallation neutrons are moderated and subsequently directed to neutron scattering instruments for materials research, rather than being absorbed for producing neutron transmutation reactions in a waste blanket, as in ATW technology.

Key issues in the target/blanket module revolve around radiation damage by the proton beam and by the neutrons generated in the heavy metal target, as well as compatibility with the liquid metal coolant, or with water in the case of a solid tungsten target. Satisfactory lifetimes of the components in the radiation, thermal and chemical environment must be ensured. Materials performance will determine the feasibility, reliability and economic cost of this technology. Target containment and structural materials will need to be identified and subjected to experimental radiation effects studies and compatibility testing. Analysis and modeling must be an important part of this work in order to make use of irradiation results from materials irradiated in spectra different from spallation spectra, such as the huge amount of data already available from research reactors, LWRs, and charged particle irradiation experiments. LBE loops will need to be fabricated to study compatibility issues in unirradiated materials. Ideally, in the research and development for ATW, specimens should be subjected to high energy proton fluxes while under stress and immersed in high velocity, high temperature LBE in order to better simulate the synergistic effects that will be encountered in the actual application.

Exposure of materials at spallation neutron sources to the incident protons and spallation neutrons can be shown to produce much more hydrogen, helium, and heavier transmutation species than is the case for exposure to fission neutrons. Most of the transmutation products are produced by the proton beam and by the high-energy tail of the neutron spectrum. Except for this high-energy tail, the spallation neutron spectrum is otherwise not drastically different from a fast fission neutron spectrum. This additional burden of radiation-produced impurities can be expected to exacerbate radiation damage. Calculations give production rates of helium and hydrogen up to about 100 appm He/dpa and 1000 appm H/dpa; by contrast, the ratio for fission reactor irradiations is less than 1 appm He/dpa and for fusion reactors it is about 10 appm/dpa for both H and He. Radiation induced swelling may be a significant issue for the contemplated temperatures of the target/blanket module. Hence swelling should be investigated in the temperature range and for the candidate structural materials anticipated for ATW design and operation. Irradiation creep is relatively temperature insensitive and, therefore, will occur at the temperature of operation of the ATW. Whether it is a significant life limiting issue will depend on the design of the target. An open structure will not pose as many problems as a close fitting array of rods with small gaps and fine tolerances, for example. The interactions of these dimensional instabilities, radiation induced swelling and creep, will need to be understood and the consequences assessed in R&D leading to the deployment of the ATW. There is a reasonably well developed background on these two phenomena in terms of both theory/modeling and fundamental experiments [3]. Radiation embrittlement is expected to be an issue that may be important and which must be dealt with by materials selection and design based on theory and modeling and new experimental knowledge.

Liquid metals can be aggressive media, and corrosion and compatibility studies must be included in the research and development program as mentioned above. Two issues should receive particular attention: liquid metal embrittlement and temperature gradient mass transfer. In the former, grain boundaries may be sites of increased penetration and crack initiation by the LBE, especially under stress. In the latter, generalized corrosion may occur, in which structural materials are preferentially dissolved at higher temperature regions and re-deposited at lower temperature regions of the module. In the extreme this process may lead to flow blockage or structural compromise of components.
The effects of irradiation on these processes are presently unknown but may be significant in terms of synergistic degradation processes.

A surveillance program for ATW materials should be planned, in which target materials are located in or near the target and removed periodically for materials characterization and testing.

References:

1. Report to Congress, "A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology, DOE/RW-0519, October 1999.

2. International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, NV, July 1994, AIP Conference Proceedings 346 (American Institute of Physics, Woodbury, NY, 1995).

3. L. K. Mansur, "Theory and Experimental Background on Dimensional Changes in Irradiated Alloys", J. Nucl. Mater. 216 (1994) 97-123.

MECHANICAL BEHAVIOR, PREDICTIVE MODELING AND COMPUTER SIMULATION

The loss of fracture toughness and ductility, along with the deleterious effects of creep, swelling, and stress relaxation are of critical importance to reactor safety, lifetime, and performance. No unified model covering all length scales can successfully explain either deformation or fracture. Dislocation theory has achieved some success on a microscopic length scale; continuum elasticity and constitutive equations that are based on it have achieved some success on a macroscopic length scale. What is lacking is a unified model that can effectively incorporate aspects of both dislocation theory and elastic-plastic continuum models at the critical interval between typically 0.1 micron and 10 microns, where these highly successful models do not converge. Note that this interval corresponds to the size regime of microstructural features that may be controlled by appropriate synthesis and processing parameters.

It is still not possible to formulate an accurate theory of work hardening or dislocation cell formation during deformation. Incorporation of alloying elements and secondary phases is handled by sophisticated empiricism and requires detailed mechanical property testing to develop appropriate constitutive relations suitable for finite element models.

There is a lack of understanding of the evolution of the defect state, microstructure and microchemistry associated with the cumulative damage caused by below-yield cyclic stress. However, a solid that is subjected to such cyclical stress has a "memory" for its cyclical stress history, implying that there is associated cumulative damage. The challenge is to identify and quantify this damage. Corollary challenges are to find an experimental diagnostic that can be used to characterize this damage, and to correlate this defect state with the remaining safe life before failure.

There is no first principles understanding of the concepts of fracture toughness (proportional to the energy required to propagate a stable crack) and the brittle-ductile transition. One challenge is to develop a predictive model for the calculation of fracture toughness for a given material a priori. A corollary challenge is to predict the temperature at which a material undergoes a transition from brittle to ductile fracture. The old problem of explaining such a striking variation over such a small interval in temperature in many body-centered-cubic structured metals and alloys, including ferritic steels, remains; it has never been traced to any observable changes in microstructure. Creep deformation leading to fracture is often estimated using empirical time-temperature parameters based on invalid assumptions. A first principles approach to identify and characterize the cumulative damage from applied stress and temperature is required.

There is now an unprecedented opportunity to exploit emerging computational and analytical tools for the study of fundamental issues in dislocation motion and interaction. These new tools include include massively parallel processing computer codes and machines, new techniques for establishing activation energies from atomistic calculations, and for simplifying computations involving distributed dislocations (mesoscopic scale), and in-situ X-ray techniques for direct, real-time dislocation studies (densities, types, and patterning). The anticipated advances in understanding would span the length and time scales of individual dislocation motion, the intersection of grain boundaries by dislocations, the formation of dislocation networks (the patterning problem), and the deformation of polycrystals (work hardening). We are now ready to start solving these fundamental materials science problems that are critical to developing unified, first principles models of deformation, fracture, and damage and thereby advance our understanding and control over mechanical behavior.

In addition to mechanical behavior, the ability to predict the effects of radiation, applied stress, elevated and cycling temperatures, and hostile chemical or corrosive environments over all dimensional scales is necessary to reliably forecast the performance of reactor components over long times (perhaps beyond 60 years, and certainly well beyond laboratory test durations.) Computer simulation is now nearly as powerful as experiment and theory. Simulations are used to interpret experiments, to investigate phenomena, to predict properties, and to test mathematical models. Multi-terascale computers will have a revolutionary impact on materials science in the mesoscale size range. Currently, terascale simulations using first principles quantum mechanics can model electronic structure to compute properties (bond angles, lattice parameters, thermal expansion coefficients) of ideal crystals and non-crystalline systems containing up to several hundred atoms. Other quantum mechanical methods, which sacrifice some accuracy and reliability by using parameters derived from fits to first-principles results or experiment, are able to simulate systems containing thousands of atoms. At the critical intermediate length scale discussed above, a trade-off between accuracy and model size has been necessary to simulate collective phenomena that transcend several thousand atoms. At the continuum level, simulations use experimentally derived constitutive and elasticity equations to model physical structures and macroscopic processes, typically using finite element methods.

However, predictive models at the continuum scale must be based upon more rigorous fundamentals, which requires multi-terascale computing. It is crucial to couple first principles electronic and atomistic calculations to mesoscale simulation, and then to finite-element continuum calculations, in order to simulate bulk materials properties accurately.

The ability to simulate those microstructural features that are essential to performance will make it possible to understand the relationship between synthesis, processing, structure and performance. As discussed above, many important properties of materials are determined not at the atomic scale, but by collective phenomena involving large numbers of interacting atoms. Furthermore, materials processing frequently controls features at the mesoscale, such as grain size, to optimize a desired property. Rigorous simulations of complex materials and their time-dependent behavior in the hostile environment of a reactor will lead to the development of new and improved materials, and thus enable safer, more environmentally benign, longer operating, better performing and economically superior reactors and radioactive waste containment systems.

RADIATION EFFECTS

Radiation effects result from the interactions of neutrons, fission fragments, electrons, ions and gamma rays with materials. Radiation-induced changes in the microstructure, defect-structure and microchemistry greatly influence the lifetime-limiting corrosion and mechanical behavior of nuclear-reactor and power-accelerator components. These effects include enhanced diffusion, phase transformations, restructuring (as in the rim effect), loss of mechanical integrity such as fracture toughness or ductility, accelerated corrosion, significant swelling, and decreased thermal conductivity. Historically, research into these changes, known as radiation effects research, has made major contributions to fundamental scientific advances in understanding, e.g., the impact of lattice defects on materials properties, atomistic modeling of solid-state systems (including the development of computer simulation and of more accurate interatomic potentials), and the development of sophisticated technological methodologies such as ion implantation and ion-assisted growth of thin films [1-4]. Unfortunately, the decreasing emphasis over the past several years in the United States and Europe on nuclear technology has created a situation where many laboratory and university programs in this field have either disappeared, or are in an advanced state of decline. As pointed out in the President's Committee of Advisors on Science and Technology [5], this decline must be reversed if the United States is to maintain a position of leadership in nuclear technologies and underlying scientific areas.

While much work has been done on radiation damage fundamentals in simple alloys, particularly on elemental metals in the 1960's and 1970's and on model binary alloys in the 1980's and 1990's, radiation effects in engineering steels and advanced ceramics or composites are not well understood. Perhaps this situation is best summarized by noting that in the current state of affairs for metals, where the accumulated knowledge is the greatest, it is still unknown whether the vacancy or the self-interstitial defects created in steels are more mobile. The lack of knowledge regarding radiation effects in insulators, advanced composites and ceramics is considerably worse. Hence we are far short of being able to formulate reliable predictive models of the effects noted in this report. A fundamental understanding of the mechanisms and kinetics of microstructural and microchemical evolution, and corresponding property changes, during irradiation is necessary.

The radiation-induced restructuring of nuclear fuels at high burnup and high temperatures also greatly affects their performance. To understand radiation-induced changes in macroscopic engineering properties, an atomistic understanding of radiation damage mechanisms is required. Furthermore, radiation effects occur over the lifetime of the plant (30 to 60 years, and possibly longer depending on license renewal) or storage time of nuclear waste packages (thousands of years). Fundamental radiation damage states and kinetics must be understood in order to make longer-term predictions based on data that are often obtained for shorter times and higher dose rates.

References:

1. W. J. Weber, R. C. Ewing, C. A. Angell, G. W. Arnold, A. N. Cormack, J. M. Delaye, D. L. Griscom, L. W. Hobbs, A. Navrotsky, D. L. Price, A. M. Stoneham, and M. C. Weinberg, Radiation Effects in Glasses Used for Immobilization of High-Level Waste and Plutonium Disposition, J. Materials Research, 12 [8]: 1946-1978 (1997).

2. L. K. Mansur and C. L. Snead, Jr., Proceedings of the Symposium on Radiation Materials Science in Technology Applications, Anaheim, CA, February 4-8, 1996, J. Nucl. Mater. 244 (1997) 177-310.

3. W. J. Weber, R. C. Ewing, C. R. A. Catlow, T. Diaz de la Rubia, L. W. Hobbs, C. Kinoshita, Hj. Matzke, A. T. Motta, M. Nastasi, K. K. H. Salje, E. R. Vance and S. J. Zinkle, Radiation Effects in Crystalline Ceramics for the Immobilization of High-Level Nuclear Waste and Plutonium, J. Materials Research, 13[6]: 1434-1484 (1998).

4. W. J. Weber, L. K. Mansur, F. W. Clinard, Jr. and D. M. Parkin, Radiation Effects on Materials in High-Radiation Environments: A Workshop Summary, J. Nuclear Materials, 184: 1-21 (1991).

5. Report to the President on "Federal Energy Research and Development for the Challenges of the Twenty-First Century", President's Committee of Advisors on Science and Technology: Panel on Research and Development, November, 1997.

HIGH BURNUP FUEL PERFORMANCE AND ADVANCED FUEL MATERIALS

National and international trends in nuclear fuel utilization are towards higher burnup, up to 75 GWD/MTU. There are indications of interest to eventually push the limits to even higher values. Increased burnup and longer reactor cycles have very attractive economic features. In addition, extended burnup can lead to fewer fuel assemblies that must be stored on site and ultimately disposed of in a national repository. However, higher burnup will also lead to higher activities and concentrations of transuranics, which may dictate fewer assemblies per waste package, or even alternative approaches to disposition, such as partitioning and transmutation. Furthermore, as the burnup of UO_2 fuel reaches higher levels, significant new phenomena or more extensive effects from known phenomena are being identified which must be understood and accommodated in the fuel designs, core management schemes, and operating strategies. These include fission gas release, restructuring of fuel (as in the development of the "rim" effect), pellet-clad interaction, and clad behavior.

Next-generation reactors for nuclear power may differ significantly from present designs, utilizing gas or liquid metal cooling that allow much higher operating temperatures and efficiencies. High burnup under higher operating temperatures may yield phenomena not yet observed.

Longevity of reactor fuels has a major influence on operating economics. Current fuel designs have been taken to their regulatory limits. To achieve significant increases in average core burnup requires the development of advanced fuels based on either traditional fuel materials (e.g. UO_2, or UO_2-ThO_2) or advanced fuel materials or concepts (e.g. metallic fuels, carbide fuels, pure actinide fuels, or composite fuels, including inert fuel matrices). Understanding the performance (changes in microstructure, defects, and defect distributions, and changes in mechanical, chemical, and nuclear properties) of these fuel types must progress to the stage where it can contribute to reliable predictive modeling and improved fuel lifetime. In such an endeavor, one must think beyond water-cooled systems. Fundamental understanding necessitates the capability to predict, test and verify performance under both steady-state and transient conditions. With advances in computer simulation and modeling capabilities, the performance of advanced fuel materials under operating and transient conditions will become predictable based on physical processes occurring from the atomic to macroscopic levels. This could eventually eliminate the need for long testing programs and empirical models. Significant gains will be realized by continued experimental and theoretical materials developments. Clearly, the impact of higher burnups or new fuel materials on proliferation, disposition costs, and public safety may be significant.

CLAD PERFORMANCE

Increasing demands are being placed on clad performance as fuel burnup targets are being extended. This is critical because the cladding is the first barrier to the release of radioactive fission products to the reactor coolant system and potentially beyond. In addition, envisioned burnup limits will require the development and qualification of new clad materials that meet higher performance criteria. Advanced reactor concepts that incorporate gas or liquid metal coolants, in addition to high burnup, will greatly challenge cladding performance. With rapid developments in the area of ceramic composites that do not exhibit brittle fracture, fiber-reinforced ceramic cladding may be feasible in the foreseeable future. It is critical to understand phenomena such as corrosion, mechanical properties, radiation effects, phase behavior, fretting, thermodynamic performance, and other aspects of existing and new clad materials under all conditions that may exist in future nuclear power systems. Rather than empirical performance models, scientifically based performance models will provide more reliable predictions of behavior over a much wider range of conditions, potentially at great cost and time savings. Great gains in performance and safety may be realized by materials and theoretical developments in this area.

HIGH-TEMPERATURE MATERIALS PERFORMANCE AND AGING

High-temperature materials clearly cross cut and impact many of the topics and issues discussed already in this report. The development and utilization of such materials will vary with specific application, but in all cases significant improvements in safety and reliability can be realized. Potential improvements comprise all aspects of high-temperature materials behavior including mechanical, chemical and physical properties, as well as the effects of radiation and thermal aging. Investigations are needed to explore the parameters of both existing and future operating conditions. The performance of new high-temperature alloys, ceramics and composites in reactor environments must be studied and understood well enough to permit reliable modeling of materials degradation and component lifetimes. With advances in understanding and computer modeling capabilities, scientifically based predictions of high-temperature materials behavior will become possible.

To fulfill the need for safer, more environmentally benign, longer operating (60 years and beyond), better performing, and economically superior nuclear power reactors and radioactive waste containment systems, reliable predictive models for the long-term behavior of reactor materials under the combined conditions of applied stress, residual stress, radiation, temperature, and corrosive environments are also required. Although aging, like high-temperature performance, again crosscuts many of the research needs that are described above, it too is identified here separately in order to emphasize its importance.

The significance of understanding aging phenomena is perhaps most self evident for nuclear waste forms. Considerable work has been done on radiation effects in nuclear waste forms as compared with natural materials (e.g., actinide-bearing minerals,[1,2] and the corrosion of nuclear waste glasses[3,4] .

References:

1. R. C. Ewing, W. J. Weber and W. Lutz (1996) Crystalline Ceramics: Waste Forms for the Disposal of Weapons Plutonium. NATO Workshop Proceedings, E. R. Merz and C. E. Walter, Eds., Disposal of Ex-Weapons Plutonium as Waste, NATO ASI Series, Kluwer Academic Publishers, Dordrecht, The Netherlands, 65-83.

2. R. C. Ewing (1999) Nuclear Waste Forms for Actinides, Proceedings of the National Academy of Sciences, 96(7) 3432-3439.

3. R. C. Ewing, W. Lutze, and A. Abdelouas (1998) Natural Glasses and the "Verification" of the Long-term Durability of Nuclear Waste Glasses. Proceeding of the 18th International Congress on Glass. M. K. Choudhary, N. T. Huff, and C. H. Drummond III, Eds., CD - ISBN 1-57498-053-X, American Ceramic Society, San Francisco, CA July 5-10, 1998.

4. R. C. Ewing, (in press) Aging Studies of Nuclear Waste Forms: The Evaluation of Long-Term Behaviour. Proceedings of International Conference on Aging Studies & Lifetime Extension of Materials.

CONTRIBUTORS TO THIS REPORT

This report is derived from contributions at a workshop that was under the direction of the Department of Energy's Nuclear Energy Research Advisory Committee that took place on 18 - 20 October 1999 and by extensive written electronic communications that took place over the duration from December 1999 through January 2000.

Those that contributed to the workshop on 18 - 20 October 1999 were:
Todd Allen, Argonne National Laboratory
Jerry Etheridge, Idaho National Engineering and Environmental Laboratory
Madeline Feltus, U. S. Department of Energy
Bob Gottschall, U. S. Department of Energy
Marty Martinez, Jupiter Corporation
Lee Peddicord, Texas A&M University
Lynn Rehn, Argonne National Laboratory
Bill Shack, Argonne National Laboratory
Ed Simonen, Pacific Northwest National Laboratory
Jim Tulenko, University of Florida
Bill Weber, Pacific Northwest National Laboratory

Those that contributed to the extensive written electronic communications in December 1999 and January 2000 were:
John W. Elmer, Lawrence Livermore National Laboratory
Rodney C. Ewing, University of Michigan
David W. Gandy, Electric Power Research Institute
Robert J. Gottschall, U. S. Department of Energy
Louis K. Mansur, Oak Ridge National Laboratory
Michael B. McNeil, U. S. Nuclear Regulatory Commission
K. Lee Peddicord, Texas A&M University
Lynn E. Rehn, Argonne National Laboratory
William J. Shack, Argonne National Laboratory
Edward P. Simonen, Pacific Northwest National Laboratory
R. Bruce Thompson, Ames Laboratory
R. (Viz) Viswanathan, Electric Power Research Institute
William J. Weber, Pacific Northwest National Laboratory

This report was compiled and edited by:
Lynn E. Rehn, Argonne National Laboratory
William J. Weber, Pacific Northwest National Laboratory
Robert J. Gottschall, U. S. Department of Energy

Appendix D

Working Group Report on – Reactor Technology/Nuclear Power Plant Design

Nuclear Energy Research Advisory Committee
Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report

Reactor Technology and NPP DesignWorking Group
December 8-10, 1999 Workshop

Summary Report

Reactor Technology and NPP Design Working Group
December 8-10, 1999 Workshop

Working Group Members:

John Herczeg (Chair)	DOE-NE
Roger Anderson	Northern States Power
William Andrews	PNNL
C.K. Chou	DOE-RW, LLNL
George Davis	ABB-Combustion Engineering
Harold Feiveson	Princeton University
Michael Golay	MIT
Yassin Hassan	Texas A&M University
James Hassberger	LLNL
Angus Hendrick	Naval Reactors
John Ireland	LANL
Peter Karcz	DOE-MD
James Lake	INEEL
Gordon Michaels	ORNL
Carter “Buzz” Savage	JUPITER
Arkal Shenoy	General Atomics
Michael Todosow	BNL
Gary Vine	EPRI
David Wade	ANL

Overview

The Reactor Technology/Nuclear Power Plant (NPP) Design Working Group conducted round table discussions to generate inputs for DOE-NE to consider in the development of its long term research and development program for nuclear energy, science and technology, specifically with respect to advanced reactor technologies and new nuclear power plant designs. The Working Group bore in mind the remarks that were made on December 8 by W. Magwood (Director, DOE Office of Nuclear Energy, Science and Technology) regarding Generation IV reactors and G. Rueger (Chief Nuclear Officer, Pacific Gas & Electric) regarding long term R&D needs of the nuclear utility industry. This summary report presents the input from the Working Group, arranged in near-term and long-term research needs. In general, the group reached consensus on the input, although individual members did not always agree on the subtopics, priorities or timing for specific research into advanced reactor technologies.

The summary report attempts to provide this working group’s answers to the list of questions listed in the workshop breakout session process and outcomes guidance document. The questions were:

- What DOE-NE nuclear energy mission and objectives does this working group’s R&D topic area support?

- What should the long-term role of the Department of Energy be in conducting nuclear energy R&D in this topic area?

- What specific R&D (subtopics) should the Department's Nuclear Energy Program focus on over the next decade? Identify any significant drivers for this needed R&D.

- What nuclear energy R&D will be conducted in this broad topic area outside of any DOE involvement?

- What are the challenges or barriers hindering R&D in this topic?

In addition to these questions, the Working Group was asked by Dale Klein (NERAC Subcommittee on Nuclear Technology Roadmap) to identify facility and infrastructure needs to support the research areas the group listed. Little input was developed for this question due to lack of time.

In its process discussion, the Working Group developed a list of items to aid it in applying “outside the box” thinking to the development of research ideas. The list included understanding the customer and his/her needs, the infrastructure that would be required to support the research and its availability, taking the human factors perspective into account in any new advanced designs, the recognition that any new design must be cost competitive in whatever environment it may be installed, proliferation resistance, and the need for a multi-track program for near- and long-term research.

As a result of the last item mentioned above, a dual-track research strategy was recommended, having both a near-term (next 5-15 years) and long-term (15 years and longer) component. The near-term research would be evolutionary, focused on further improvements to existing Generation III designs to bring to market in the next 5-15 years. The long-term component would be revolutionary, and include new advanced Generation IV reactor(s) research, and look into new, untried uses for nuclear energy such as supporting a hydrogen economy.

The near-term research strategic focus areas include:

- Risk-informed design and regulation
- Advanced technologies for design, fabrication & construction, including seismic considerations.
- Advanced technology development to address proliferation resistance issues associated with existing and new designs. It was felt that today’s U.S. LWR’s with a once-through fuel cycle were proliferation resistant already.
- “Smart” Equipment. This includes self-diagnostics and self-monitoring.

The long-term strategic focus areas include:

- High Temperature Technologies. This includes research into the behavior and performance of materials, fuels, and coolant systems in high temperature environments. It also includes research into high temperature energy conversion systems.

- Energy Conversion (general). Different energy conversion systems should be evaluated, such as direct energy conversion. The uses of reactor heat also should be taken into account. There may be new arenas such as hydrogen generation in addition to the traditional uses of electricity generation, process heat, and desalination.
- Fuels. Long-term research into high performance, long lived, proliferation resistant fuels should be conducted. A separate working group is evaluating this topic.

Goal and Vision Statement

The Working Group struggled with a Goal Statement, as there was no consensus whether it should contain any quantifiable statements regarding economics, market share, high level waste reduction goals, etc. The agreed to Goal Statement is:

- To develop advanced reactor technologies that will allow highly safe new nuclear energy plants that are an economically competitive (Working Group #2 Economics provide metric) energy production alternative in the U.S. and around the world, while being responsive to environmental, waste management, and proliferation concerns.

Vision Statement:

- The U.S. Nuclear Energy R&D Program will create new nuclear options for worldwide nuclear power deployment that will improve the worldwide standard of living, global environmental quality, assure energy security and contribute to the security of nations.

Attributes/Drivers

Attributes of new reactor technologies and nuclear power plant designs are synonymous with the drivers of the research. That is, the end products of the research will be new systems that have the desired attributes. The technical issues that could hinder achieving the desired attributes will drive the research. The most important drivers are cost competitiveness, safety, and proliferation resistance. In the safety area, designs and the regulatory regime must be risk-informed.

The Working Group developed the following list of attributes/drivers for new reactor technology and nuclear power plant research:

- Low cost/cost competitiveness *
- Safety/risk informed design *
- Proliferation resistance *

* Most important

- Increased plant efficiency
- Simplicity in design and operation
- Maintainability
- Research needs to evaluate the entire fuel cycle, not just the reactor
- New designs must be environmentally friendly
- Management of low and high level waste must be assured
- New systems, or at least some new systems, should be capable of multiple applications

- New designs should be applicable anywhere in the world; i.e., we should focus on both U.S. and global market needs.
- New designs must have sustainable long term fuel supplies; they must serve as both short-term and long-term solutions to worldwide energy needs
- An infrastructure must be maintained that includes facilities and personnel needed to carry out a large research program , then build and operate new reactors
- Industry as well as government must commit to investing in long term R&D
- DOE should pursue near-term and long-term R&D programs in parallel
- The long-term component of the research program should initially pursue sustained research to address the key technical issues confronting Generation IV reactor concepts – specific technology (ies) selection will take place in a later phase of the program
- Any multi-track research program should be managed as an integrated program
- The research program should be based on long-term sustained federal funding, leveraged with international collaboration
- Research scope should include large scale experiments & testing leading to prototype and demonstration plants
- An independent oversight group should be established to integrate and assess this research, as well as all other research conducted by NE.

Barriers/challenges

There are several barriers and challenges to performing a long-term nuclear technology research program. The Working Group discussed the following:

- **Stable, multi-year funding.** All participants sponsoring the research must provide stable, multi-year funding in order to maintain a long-term research program. This would include DOE, industry and international collaborators.

- **Lack of consensus.** Because of the uncertainty of the future role of nuclear energy to meet the world's energy needs, a lack of consensus exists as to projected research needs and how to meet them. With the ongoing keen competition for research funds, a united approach to research from all sponsors will be necessary.

- **Facility availability.** Research facilities around the world are aging, and plans to replace or upgrade them to meet future research needs are difficult to predict. The Nuclear Technology Roadmap subcommittee of NERAC is assessing projected facility needs to conduct long-term nuclear R&D. The two subcommittees need to work closely in order to ensure that gaps in projected facility availability are identified and plans to close the gaps are included in the research plan.

- **Personnel**. Personnel availability to carry out a large research program, then build and operate new reactors will be a challenge. Issues include retirement of senior researchers and the declining ability to attract and retain young scientists and engineers in the nuclear technology fields.

- **Insufficient industry investment in long term R&D.** Industry is currently able to fund the short-term research that is needed to help maintain current plants operating safely and profitably. Industry is interested in helping identify long-term R&D needs, but has limited ability to fund long-term research at this time. This was emphasized in Greg Rueger's talk. To interest industry to commit to investment of funds for long-term research is a challenge to DOE. A shift in regulatory environment as well as economic incentives will be required.

Long Term Role of DOE

The group generally felt that DOE should take the lead for initiating and maintaining a long-term nuclear energy R&D program. It should leverage its investment with participation and funding from industry and international collaborators. The institutional issues of high level waste management and recycling of spent fuel must be addressed by DOE since they will impact decisions on advanced reactor technologies selection.

R&D Needs

The Working Group concluded that a dual track approach to the research program in reactor technology and nuclear power plant design is appropriate. Both near-term and long-term research, as defined above, should be pursued. The focus of each of the two efforts would be different.

The group generated a list of generic research areas to be pursued, many in both the short- and long-term research paths. A few were recognized as being especially important, but no further attempt was made to prioritize the generic research areas.

- High temperature materials *
- High temperature fuels *
- Energy conversion technologies *
- Risk-informed design and regulation *
- Fabrication and construction technologies *
- Controls/Information Technology
- Alternate applications (other than electric generation)
- High level waste burners
- Coolant technology
- Process heat
- Recycle technology
- Large capacity reactors
- Small capacity reactors

- Thermal and fast neutron spectra
- Thorium and other cycles
- Peaking plants
- Computational methods
- Chemical processes
- Reactivity Control
- Passive safety
- Human factors

* High priority

The group felt that near-term research should be conducted in the following topic areas:

- Virtual construction, life-cycle information management, and fabrication/construction technologies *
- Risk-informed design & regulation *
- Smart equipment *
- Seismic design *
- Higher burnup fuel
- Reliability engineering
- Virtual reality testing
- Small reactors
- D&D technologies
- Analysis methodology for design & safety
- Fuel forms

* High priority focus areas

The long-term component of the reactor technology/nuclear power plant design research program would initially focus on the development of high temperature materials, coolants and fuels, energy conversion technologies and fuels in general. Later on in the program, the emphasis would eventually shift to the development of one or more specific reactor designs. Large scale testing might occur before specific designs are selected, but prototypes and demonstration plants would not be built until designs have been selected and developed adequately. The group agreed that any new reactor concept that gets selected for development must be pursued through design certification by the Nuclear Regulatory Commission. This would apply to designs intended for export or domestic applications.

The long-term research program might lead to the development of one or more new designs of advanced water reactors, gas-cooled reactors, or metal-cooled reactors. In addition, several other concepts were discussed for possible development, including molten salt reactors, liquid fueled reactors, advanced high temperature reactor designs, gas-fueled reactors (e.g. ultra-high temperature), large capacity reactors (many gigawatts), and subcritical reactors. Specific research areas were identified and prioritized by the group for water, gas and metal cooled reactors and are listed below. This level of detail was not completed for the other concepts mentioned.

Long Term Research – Water Reactors

- Superheated and super-critical steam systems *
- Long life fuels/new fuels/fuel forms(R) *
- New core assembly configurations, including fast spectrum cores (R) *
- Heavy water systems? (This may be a non-starter because of proliferation concerns)
- New energy conversion systems (R) *
- Recycle technology
- Advanced steam generators (R) *
- Small reactors (100-300 MWe) (R&D) *
- Advanced claddings
- Advanced structural materials
- Severe accident mitigating systems
- Containment systems

* High Priority R – Research D - Development

Long Term Research – Gas-cooled Reactors

- Magnetic bearings (D) *
- Helium turbomachinery (D) *
- High voltage connectors
- Helium recuperators (R&D) *
- Pre- and inter-coolers
- Insulators (R)
- Non-metallic control rods (R)
- Demonstration of passive safety systems
- Carbide fuel recycle
- Ceramic fuels (R) *
- Systems analysis
- Chemical reformers
- Multi-unit digital controls

Long Term Research – Metal Cooled Reactors

- Materials compatibility with coolant (R) *
- Pb, Pb-Bi, Na, and Hg coolant technology
- Reactivity controls
- Basic nuclear data (R) *
- Corrosion control
- Fuels (R) *
- Direct contact heat exchangers
- Passive safety systems
- New energy conversion technologies (e.g., direct, gas) *
- Recycle schemes (R) *
- Critical experiments

Recommendations

The Working Group made the following recommendations regarding a long-term research program in reactor technology and nuclear power plant design:

- DOE should pursue a dual track, and conduct a near-term and long-term R&D program in parallel
- The program should initially pursue sustained research to address the key technical issues leading to Generation IV reactor concepts. A focus on high temperature behavior of materials, coolants and fuels, and energy conversion systems is suggested. Selection of specific Generation IV reactor designs to develop, test, demonstrate and build should be delayed to a later phase of the program.
- The program should be managed as an integrated program
- Any long-term research program should be based upon long term sustained federal funding, leveraged with international collaboration
- The scope of the research program should include large-scale experiments & testing, even in the early phases before selecting specific reactor designs to develop.
- DOE-NE should establish an independent Office of R&D Integration and Assessment. This office should conduct planning, analysis and independent external oversight of all NE research programs. It would provide direction to keep the research programs focused on energy security, projected customer needs, leverage industry and international participation, and eliminate redundant research among various internal and external organizations.

Appendix E

Working Group Report on – Nuclear Plant Economics

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Nuclear Power Plant Economics Working Group
Dec 8-10, 1999 Workshop

Table of Contents

NPP Economics Working Group Charge and Scope

Charge: Provide input to a long-term R&D plan whose projects reach fruition in 2015-2020. This is when the ten-year U.S. design certifications for Generation III built overseas will first expire and need to be renewed, and when preparations may begin for demonstration of a Generation IV reactor in the U.S.

Scope: NPP Economics R&D includes advancements in methodologies and technologies associated with the design, fabrication, manufacturing and construction, and operations and maintenance of nuclear plants to reduce costs. We primarily focus on actions that the DOE can take over the next 20 years.

Objectives for Generations III and IV

A number of tough market objectives for Generation IV were suggested:
- A price goal of 3¢/kWhr (breakdown given below). This is the overall objective, with suggested cost and performance targets given below.
- Capital cost of $750/kW (overnight).
- Thermal efficiency greater than 50%.
- Construction time less than 24 months.

A number of achievable market objectives for Generation III were suggested:
- A price goal of 3.5¢/kWhr, down from 4.1¢/kWhr projected for the early units.
- Capital cost less than $1200/kW, down from $1500/kW for the early units.
- Efficiency of 36%, up from 33% for the early units
- Construction time of 30 months, down from 36 months for the early units.

Natural-gas-fired combined cycle competitive economics, which will have to be met, were suggested:
- A price of 2.5–3.3¢/kWhr.
- Capital cost of $580/kW.
- Efficiency of 55–60%.
- Construction time of 24 months.

For purposes of program planning, it is assumed that the fossil plant competition will not be hindered by cost internalization of their green house gas emissions or by a carbon tax and that fossil fuel supply and price will remain stable.

Set an aggressive schedule for the R&D program, although it goes against the prior experience (a proposed schedule is developed next).

Proposed Phasing of the Generation IV Program

Research 2000–2005

Investigation of multiple technologies. This will require much more funding than the Nuclear Energy Research Initiative (NERI) by one order of magnitude—$200M/yr—and maybe more time. The first phase is an expanded NERI in both magnitude and scope which should provide the basis to select the two most promising technologies for intensive development. Due to the federal budget cycle, it cannot start before FY 2002, and may need more than five years to the downselection of technologies for the next phase.

Development Phase I 2005–2010

Downselect to two technologies, based on projected risk-adjusted cost. Address regulatory issues.

Development Phase II 2010–2015

Testing of components and subsystems. Licensing of full design.

Demonstration 2015–2020

Construction of full-scale prototype. Financing by either the federal government or an industry/government partnership.

Deployment beginning in 2020

Drivers of NPP Economics

Economic Drivers are the Primary Issue for the Generations III and IV

- Capital Cost
- Efficiency
- Capicity Factor
- Construction Time
- O&M Cost
- Additional Applications

Proposed R&D Topics to Address Each Driver

1. ***Total capital*** [the numerator in $/kW]. Alternative: MW per unit volume of the plant.

Value	Urgency	R&D Topic/Subtopic	Generation
1	B	System optimization:	IV
		Optimization of module size and configuration, and major components	
		Volume and footprint minimization, system optimization through systems engineering and trade studies	
		Unique approaches to modularity (for example, modules built up with variable numbers of components fit within an overall envelope, allowing the system to have a selectable electric output, etc.)	
1	C	Repowering reactors (internals replacement/upgrade following end-of-life)	II
2	B	Containment liner technology (significant cost reduction is needed over steel lined concrete–e.g., with advanced coatings).	III, IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

2. ***Efficiency*** [determines the denominator in $/kW]. Alternative: Electrical output.

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	Alternative cycles (possibly with alternate moderators):	IV
		Supercritical fluids	
		Direct cycle gas turbine (helium)	
		Liquid metal high temperature	
		Direct conversion of fission fragments to electricity	
1	A	Improved materials focused on high temperature performance	III & IV
2	A	Topping cycles (combustion superheating) to be added to nuclear steam cycles.	III & IV
2	A	Working fluid technology	
2	B	High efficiency turbines	III & IV
3	B	Bottoming cycles:	III & IV
		Desalination	
		Cogeneration	
3	B	Adjusted thermal margins (i.e., better understanding of margins through additional analysis)	II, III & IV
3	B	Power upgrade to current plants through improved instrumentation, and/or improved fuel design	II

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

3. Capacity factor

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	High burnup fuel (analysis and testing)	II, III & IV
1	A	Advanced sensors	III & IV
1	A	Advanced surveillance and diagnostics	II, III & IV
1	A	Aging management	II, III & IV
1	B	On-line maintenance	II, III & IV
1	B	Improved major component reliability (steam generators are a major aspect of Generation IV liquid-metal-based concepts)	II, III & IV
1	C	Predictive maintenance and artificial intelligence	II, III & IV
2	A	Improved in-service inspection (ISI) for major (10 yr) outages	II, III & IV
2	C	On-line refueling (This was reduced in priority due to the potential for proliferation and licensing issues.)	II, III & IV
3	C	Outage optimization	II, III & IV
3	C	Supply chain management (Just-in-Time practices, etc.)	II, III & IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

4. Construction time

Value	**Urgency**	**R&D Topic/Subtopic**	**Generation**
1	A	Virtual reality for design, construction, etc.	III, IV
1	A	Procurement process control and automation	III, IV
1	A	Computerized process management	III, IV
1	B	Modularization:	III, IV
		Erection technology (e.g., use of multiple cranes)	III, IV
		Field assembly of modules	III, IV
1	B	Welding technology	III, IV
1	B	Reduce plant commodities (such as concrete), and/or use alternative materials.	III, IV
1	C	Factory fabrication, assembly, manufacturing and certification	III, IV
2	B	Analysis and optimization of structural margins, and/or use of alternative methods, e.g., replace the widespread use of rebar.	III, IV
3	C	Complete plant fabrication (barge or submarine-based mobile power plant)	III, IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

5. Operations and Maintenance Costs

Note: Personnel, outages and equipment are the big costs here.

Value	Urgency	R&D Topic/Subtopic	Generation
1	A	Design for reduced maintenance	III & IV
1	A	Waste management technology (e.g., dry storage of spent fuel)	III & IV
1	A	Improved I&C hardware and software	III, IV
1	B	Risk-informed regulation	II, III & IV
1	C	Staff size optimization	III, IV
1	C	Predictive maintenance	II, III & IV
2	A	Improved decontamination technologies	II, III & IV
2	B	Improve ISI technology and regulation	II, III & IV
3	A	Coolant chemistry control	II, III
3	B	Decommissioning	II, III & IV
3	C	Outage planning	II, III & IV
3	C	Supply chain management (e-commerce, JIT, etc.)	II, III & IV
3	C	Standardization	III & IV

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

6. *Additional Plant Application and Byproduct Revenues*

Value	**Urgency**	**R&D Topic/Subtopic**	**Generation**
3	B	Hydrogen production from process heat	
3	B	Materials production for space (Pu-238) or defense needs	
3	B	Process heat	
3	B	Medical and industrial isotope production	

Value: 1 = High (significant contributor to achieving goals), 2 = Medium, 3 = Low (but still worth undertaking)

Urgency: A = High (begin now), B = Moderate (can delay for a few years), C = Low (can delay until a later phase of the program)

Also mentioned in this category, but not rating any priority, were:

- Process steam
- Hydrogen via electrolysis (presumably in off-peak hours). This was not viewed as being distinct from any other electric generation capability being coupled with hydrogen production.
- Energy storage / nuclear-based renewables
- District heating
- Desalination

These were not rated because nuclear power does not provide a unique capability different from alternative electric generators. These applications none the less would enhance the overall benefit of nuclear power through its contributions to a broader energy sector than electricity.

7. Applicable Generic R&D Topic Areas

Of significant value is the application of on-going generic R&D, both within and outside the nuclear community, to the Generations III and IV development. The following chart summarizes these generic R&D topic areas and suggests their priorities in terms of the potential contribution to the economic drivers of Generations III and IV.

		Economic Drivers and R&D Topic Areas				
	Total Capital	**Plant Efficiency**	**Capacity Factor**	**Construction Time**	**O&M Costs**	**Other Applications & Byproducts**
Objective:	**$750/kW***	**> 50%**	**> 90%**	**2 years**	**3¢/kWhr****	
Overall Value	**1**	**1**	**2**	**2**	**3**	**3**
Research Priorities:						
Advanced Simulation	A	B	B	A	C	C
Construction Processes	A	C	C	A	C	C
Coolant Technology	B	A	B	C	C	C
Digital Technology	A	B	B	A	A	C
Human Factors	B	C	A	C	B	C
Information Technology	B	B	B	A	A	C
Low-Level Rad Health Effects	C	C	B	C	B	C
Materials	B	A	B	C	C	B
Mfg/Const Technology	A	C	C	A	B	C
Non-proliferation Technology	B	C	C	C	C	C
Nuclear Fuels	B	A	B	C	C	C
Operator Training	C	C	B	C	B	C
Reactor Analysis	C	B	B	C	C	C
Regulatory Reform	B	C	B	A	B	C
Robotic Technology	C	C	B	B	B	C
Safety Technology	B	C	C	C	B	C
Sensor Technology	B	A	A	C	B	C

Overview of the Relationship between R&D for Reactor Generations

Generation I

D&D is the central R&D issue today. Lessons learned are valuable for future generations and 'flow into' (i.e., benefit) them.

Generation II

O&M costs, safety and aging mitigation (capital additions) are the central R&D issues. Again, lessons learned and technologies will flow into future generation. Regulatory research is active, too, with risk-informed approaches that will improve the economics.

Generation III

Construction economics and O&M costs are the central R&D issues. Improvements are also flowing from the regulatory improvements ongoing. The forefront is modular design, virtual construction, and advanced project management. Starting in 1985, the first Generation III plant was designed and certified by NRC in 1996–a total of 11 years was required to do an evolutionary cycle. Based on that design and the NRC licensing reviews preliminary to certification, the plant was constructed in four years in Japan. Breeders as an example, spent 20 years in development and never completed a demonstration in the U.S., although a breeder demonstration plant and large-scale prototype were built and operated in France.

Generation IV

The central issue is, "What technology is most compatible with a global market economy?" The expectation is that with a substantial technology step from Generation III to IV, we will have some process improvements that flow from III to IV, but not all such improvements will be relevant. New areas will be needed, such as modular construction for nuclear plants being demonstrated in the U.S. Generation IV will hinge on (1) capital cost reduction and (2) the reduction of investment risk from waste management, safety, and non-proliferation issues.

Discussion

The first three generations were based on a technology that came primarily from submarine propulsion (i.e., LWR) technology. Generation IV may very well not be a light-water-based technology. Also, Generation II will still be needing license extension approvals at the time Generation IV is reaching definition. The R&D program will need to contain aspects of generations II, III, and IV, although much more heavily weighted to the latter than the former.

Generation IV has the opportunity to be based on a new, fresh approach. R&D can be structured logically with criteria, and with adequate technology choices. The model for the development of the program for Generation III was similarly structured, and could be used.

Comments on Related R&D being done elsewhere

Two countries are working on supercritical fluid thermal cycles.
One vendor is reportedly working on a steam turbine for NPPs with 4% higher efficiency.

Conclusions and Recommendations for the Presentation

Slide 1: Title page.
Slides 2 & 3: Cost is the fundamental barrier, and all objectives must support cost competitiveness. Objectives were formulated for Generation IV versus cost drivers.
Slide 4: Assumption–No easement of the challenge will take place through leveling of the playing field (i.e., carbon tax), although this may eventually come through slow, regulatory pressure.
Slide 5: Schedule should be aggressive. A schedule with phases was formulated.
Slide 6: The historical and future trend will be that research on early generations will almost always flow down to benefit later generations.
Slides 7–12 R&D topic areas were organized with respect to the drivers. Priorities and target generations were detailed. Other breakout sessions may have developed areas or groups of our topic areas in more detail.
Slide 13: General topic areas shown as a matrix that we intend to fill in.
Slide 14: Conclusions:

- Cost is the major barrier. DOE needs to embark on an ambitious R&D program to surmount the barrier, setting goals and striving to achieve them on an aggressive schedule.
- We have considered a general set of R&D areas. Priorities allow the selection of R&D areas to fit within the budget. Budget must be an order of magnitude above NERI, starting in FY 2002. This R&D program must be virile.
- An objective means of projecting the costs of various concepts is vital to the evaluation of the R&D projects.
- Downselection of Generation IV technology should happen about 3–5 years after a well-rounded set of technology concepts are seriously undertaken.
- The R&D program, and many policies of the U.S. government, will be greatly supported by international collaboration. The U.S. must be a serious “player” in Generation *R&D* to expect meaningful international collaboration.

Initial Comments

At the outset, each participant had an opportunity to comment on the process and/or the topic area. The comments were as follows:

- NPP competitiveness needs to get away from only being viewed in terms of economies of scale, and more into understanding the larger factors and interactions in the market framework.
- NPP is undergoing globalization. We need to understand how the U.S. fits into the world market framework.
- We need to think 'out of the box' in terms of what the power producer wants to buy, and then go after major improvements to halve the cost.
- Our group is very different from the others, we need to take into account the market factors that will set the targets that the R&D is to meet. We need to elaborate on the ground rules for reactors in that time frame.
- We must not just focus on Generation IV, because Generation III must succeed prior to the period 20 years out.
- We should depart from traditional 30 yr levelized busbar cost analysis–look at the desire for capital investment in terms of what would need to be considered to reach a decision by an executive today.
- We must stay focused on the domestic market, where Generation III is not competitive with combined cycle natural gas plants.
- The most important (Pareto analysis) factor is the plant capital: The current Generation III cost breakdown is 4.1¢/kWhr = 2.7 capital (based upon11% finance pre-tax real rate of return)+0.5 fuel + 0.8 O&M + 0.1 waste disposal + D&D. This is a 30 yr levelized cost analysis breakdown.
- One must look at the full 'going forward' costs, including general an administrative (G&A), capital additions, O&M and fuel costs–also referred to as production costs. This is about 3.5¢/kWhr. Also, the locational marginal prices need to be considered by completing a regional analysis. Each new plant must justify itself on its own expected revenues on a project basis, case by case. Locational market prices vary with the season of the year, with available local generation, existing demand and transmission capacity.
- Capital costs are tough to reduce, due to fundamental needs for radiation shielding, etc. The most important gain to be made is on reducing the lead time for construction. Also, there will be beneficial effects from R&D on project organization and finance.
- The playing field needs to be leveled with other energy sources, specifically with a full accounting of effects on the environment.
- Systems with hydrogen generation features may hold some benefit and should be studied.
- Prediction of the market 20 years out is difficult, if not impossible. Also, our long-term view may not be able to account for very new and diverse technologies (the impact of nanotechnology, e.g.) that will bring large improvements.
- There may be paradigms that can be broken in the nuclear industry, such as how one must build and test before deployment . The Boeing 777 aircraft was flown without testing, for example.
- The politics and cost of public acceptance need to be addressed in the economics.
- Economics must address the big uncertainties, which ultimately get translated into conservative assumptions. Also important are achieving very high reliability and standardization.
- Good advantages will come from design simplification, fewer parts, smaller components, reduction of machining of weldments, advanced methods of placement and insulation of rebar, and similar factors.

- Economics of all fuels must be analyzed with all of their real costs (even nuclear).
- Assuming nuclear is competitive in the future on a cost basis, there is still the consideration of the capital investment being at risk for a longer time until the plant becomes operational.
- The path to Generation IV is probably found going through Generation III plant introductions in Asia. That is, they will be linked.
- Observe that O&M costs were 'solved', i.e., greatly reduced by the industry, not by the plant design.
- Forecasts and models are very dismal on the environmental impacts of greenhouse gases, thus, the force for change to a preference for nuclear is already in action now.
- The challenge is to compete with gas-fired combined cycle plants having a capital cost in the range of $500/kW, which is equivalent to about a1¢/kWhr advantage. O&M adds 0.3¢/kWhr. Fuel costs of 1.7–2.0¢/kWhr are typical of the gas-fired competition. So current projections on natural gas prices yield a total generation cost of about 2.5–3.3¢/kWhr. No G&A or capital addition costs apply to these plants. This also assumes 6,000–6,600 BTU/kWhr heat rate (i.e. 55-60% thermal efficiency). There was some question of whether the turbine technology to achieve this efficiency was adequate. There was general consensus that the target competitive cost for Generation IV should be set at 3¢/kWhr. This is 1¢/kWhr lower than optimistic nuclear generation costs for plants that are being built now.
- The gap in nuclear/fossil plant economics would require a carbon tax of about $100/ton (for each 1¢/kWhr difference in generating costs) to bring nuclear (Generation III) into the same cost as combined cycle natural gas. There was some question about the elasticity of demand with these large proposed pricing changes. The conclusion is that carbon taxes are not likely to achieve a closing of the gap.
- Generation III could conceivably consider 'way-out' thermal efficiency improvement from supercritical steam cycles, for example, as a way of reducing the capital cost per kWhr.

Ideas and Debate

- A good potential idea is centrally-manufactured plants that are transported to the generation site (reactors using submarine reactor technology, for example). An ‘oldie but goodie’. Some doubt was raised about the economic viability of this idea. There are also a number of new problems involved with this idea in that the required high enrichments (HEU is typically required) will cause trouble with regulatory acceptance and proliferation resistance.
- Bring new innovations in technology to the nuclear business. Assembly and construction advances, for example. Procurement processes and inventory controls should be advanced, too. There was some question about whether this was really a long-term need, or whether the technology in these topics would be more likely improved in the near term.
- Study opportunities to bring major advances in other field to bear on the R&D program for Generation IV. Suggested subjects were nanotechnology, advanced simulation, advanced sensors and safeguards technology.
- Study graded quality assurance of equipment, a current issue with NRC but one that DOE should devote resources to. A number of similar ideas have been deemed acceptable to NERI, for example. These include virtual construction, satellite communications uplink of project information to and from the job site, etc. Other R&D topics are found in the areas of construction simulation, etc.
- Supply chain management should be studied.
- DOE should establish a center of excellence to highlight and encourage more of the process-related R&D. Perhaps SNL would be a good focal point, due to its involvement in several projects of this type.
- Capital cost reductions–is modularization likely to achieve the goal? For example, 100 MW modules can be delivered to a site on a flatbed truck with attendant savings. Small modules may also fit better with the generation demand of developing economies. However, a factor of 10 reduction in size may equate to a factor of 3 increase in the loss of economy of scale. In response to this it was noted that the cost of equipment is not very affected by the module size, in fact. The big savings in modularization is actually found in the reduction of the time of construction.
- Study the optimal size module. Small modules hold a promise, but the target size needs to be optimized. Factor in the value of (and constraints inherent in using up) existing nuclear sites, too. An existing nuclear site is valued at about $100/kW. However, a number of small modules may require a larger footprint than large modules, and small modules may require more sites, ‘disturbing’ more of the population–this has been a problem in Japan.
- Develop ways to evaluate the projected economics of very diverse concepts that will be proposed for Generation IV in a fair and objective manner. Bring this to bear on the selection of NERI projects that are aimed at Generation IV. A good costing system should be available (at an independent laboratory or other entity).

- ANS ‘Economic Imperative’ exercise: Compete with the best current options, with no sudden fixes like carbon credits. The MIT project is in the lead, which is a He-cooled, pebble bed 100 MW reactor. It is based on an assumption of 50% thermal efficiency. They claim it can be built for $1000/kW. Credibility? The plant has no containment (other than the outer fuel layer—this will be hard to sell in the U.S. It is hard to imagine the whole plant costing only $100M. South Africa has reportedly spent $16M on this concept, after Germany got out. This is the most credible idea of the exercise, however.
- Berkeley has a Pb/Bi cooled reactor concept.
- Proliferation resistance may significantly weaken the NPP economics.
- International collaboration: Manufacturing has to go global.
- Anticipate the bureaucratic processes: DOE should begin working regulatory approval of Generation IV, similar to what was done with Generation III.
- NERI is not funded sufficiently to bring any project to a defensible conclusion in five years.
- We should develop the economic attributes expected of Generation IV.
- Typically the plant is built with sufficient margin for 110% output, which can often be exploited later.

Clarifications / Questions and Answers

- Should we consider overseas economics, or just U.S.? A: No, we are free to consider both.
- What’s the purpose of this R&D that we recommend? To facilitate a new U.S. reactor construction, for example? A: This would provide a considerable focus. We should recommend objectives.
- Where should we draw the line on using sparse DOE funds to advance process R&D that is of great benefit to others involved with major construction projects? A: It’s important to leverage with other industries.
- Are we too focused on LWR technology? (not answered)
- Can we look and advise beyond 2020? A: Yes.
- What is the incentive of Generation IV? A: It is the logical follow-on to a Generation II or III plant. It may also produce more than just electricity (e.g., hydrogen, process heat, high fuel conversion…).

Participants in the Nuclear Power Plant Economics Working Group

Alvin	Ankrum	PNNL	alvin.ankrum@pnl.gov
Ralph	Bennett	INEEL	rcb@inel.gov
Jake	Blanchard	U Wis. Madison	blanchard@engr.wisc.edu
Tom	Blejwas	SNL	teblejw@sandia.gov
Chaim	Braun	Altos Mgmt.	chbraun@earthlink.net
Harold	Dodds	U Tenn. Knoxville	hdj@utk.edu
Stan	Hatcher	Hatcher & Assoc.	shatcher@idirect.com
Dean	Pedersen	ANL	pedersen@anl.gov
Geoff	Rothwell	Stanford Univ.	rothwell@leland.stanford.edu
William	Sailor	Stanford Univ.	sailor@leland.stanford.edu
Phillipe	Savelli	OECD NEA	savelli@oecd.org
Robert	Schock	LLNL	schock1@llnl.gov
Ronald	Simard, Jr.	NEI	rls@nei.org
John	Taylor	EPRI	jjtaylor@epri.com
Richard	Turk	ABB CE	richard.s.turk@us.abb.com
Robert	Vijuk	Westinghouse	vijukrm2@westinghouse.com

Appendix F

Working Group Report on – Reactor Safety, Component Reliability/Performance Improvement and Aging

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Reactor Safety, Component Reliability, and Aging Working Group
Dec 8-10, 1999 Workshop

SUMMARY REPORT

DOE Long-term Nuclear Energy R&D Plan Working Group on Reactor Safety, Component Reliability, and Aging

Dr. Joseph Comfort, Arizona State University, Workshop Leader

Working group participants:

Todd Allen, Argonne National Laboratory
Deborah Bennett, Los Alamos National Laboratory
W. Gary Gates, Omaha Public Power District
Dave Hill, Argonne National Laboratory
John J. Hutchinson, ComEd Nuclear Generation Group
Natraj Iyer, Savannah River Technology Group
Barclay G. Jones, University of Illinois at Urbana, Champaign
Jim Lang, Electric Power Research Institute
Alan Levin, U. S. Nuclear Regulatory Commission
David Moses, Oak Ridge National Laboratory
Upendra Rohatgi, Brookhaven National Laboratory
Theo Theofanous, University of California, Santa Barbara
Robert S. Walker, Baltimore Gas & Electric

This report summarizes the discussions and recommendations of the Working Group #3 on Reactor Safety, Reliability, and Aging at the DOE Long-Range Nuclear R&D Workshop held in Washington, D.C., December 8-10, 1999.

Initial Question

As the working group got underway, a very important question was raised. How can the Working Group form a list of R&D topics when:

- The methods for dealing with the issues of safety, reliability, and aging depend on the specific reactor design, materials to be used, etc., and
- No specific long-term design or goal has been stated or identified.

It was noted, for example, that issues of corrosion would depend on whether the reactor was of a light-water design, a liquid-metal design, or something else, and on the interactions of the coolants with the materials utilized for the core and container. Once the design goal had been specified, the R&D could be tailored to provide the optimal cost and performance features.

Approach Taken

In resolving the question, it was agreed that the Working Group would focus primarily on enabling methods and enabling technologies. Research that was directed to important areas of fundamental science and engineering would provide a common base of knowledge for application to current and any future reactor designs. A number of shorter-term topics were also identified, primarily related to the information base which underlies the regulatory environment.

The Group did not attempt to identify topics individually for the issues of safety, reliability, and aging. It was recognized that these issues were not entirely distinct and that the enabling methods and technologies would have broad applicability. Participants associated with commercial power plants identified a number of items where the lack of fundamental knowledge necessarily led to conservative operating standards which limited plant efficiencies and enhanced costs. An enhanced scientific knowledge base would reduce the uncertainties associated with many of the items.

Implications for Reactor Design

The issues of safety and reliability are critical to the design of future reactors. The designs must also be thermodynamically competitive and cost effective. Thus, the use of materials which can withstand higher temperatures (in a harsh radiation and chemical environment), and/or which can operate in environments other than water and steam will likely be very important to consider. These materials must also be highly reliable, and their reliability must be understood and well documented. A large amount of operational data related to component and system performance already exists, and these data will need to be extended, reviewed, and consolidated into reactor designs. Advanced monitoring techniques which enable timely operator intervention, along with passively-safe system and component designs will also be important for future designs.

Common Themes

Several themes came up repeatedly throughout the discussion of specific R&D topic areas.

* Critical Issues for Fundamental or Basic Science and Engineering Research:

> Common to many of the long-term topics was the importance of developing fundamental knowledge, reliable models and computational codes, and a much improved data base for testing and validating the models and codes. An incomplete understanding of the fundamental physical processes underlying the behavior or degradation of materials in the radiation and chemical operating environments of nuclear reactors and other key system components necessitates the imposition of large safety margins. With the development of new knowledge and detailed models, many uncertainties in the operations of current reactors or in the design of future reactors could be substantially reduced. The research would primarily be long-term, with intermediate-term benefits.

* Regulatory Issues:

> Due to uncertainties in our knowledge and the conservative nature of safety and reliability standards, it is believed that significant amounts of energy in the reactors are not being utilized. The potential for cost savings in current reactors or reduced costs for future reactors is quite large. It was frequently noted that ways need to be found for DOE and the NRC to work together in developing research-based data and information on licensing issues, without compromising the independence of the NRC. Such research is needed in order for DOE to obtain license approval for specific missions of the

Department, and to help make the regulations amenable to future designs and innovations.

* Multidisciplinary Aspects:

For many, if not all of these research areas, the work is broadly multidisciplinary in nature. To do such research in an effective and efficient manner, it is imperative that researchers in the various disciplines communicate and interact with one another. Effective coordination at the management level (top-down) as well as development and maintenance of a "teamwork" approach (bottom-up) is necessary. The historical pattern is poor. This concept applies both domestically and internationally, and with respect to communication with other relevant industries.

New technologies and techniques are being developed outside the nuclear power industry, and ways need to be found to adapt them to current and future nuclear facilities. While the regulatory environment currently limits some of the potential applications, it is also true that the poor state of nuclear R&D does not provide the people who could facilitate such adaptations. In particular, linkages between NE and other offices and programs in DOE, such as DP, NR, and SC, need to be established.

Common Drivers

The importance or need for many of the R&D topics were often driven by common concerns.

* Economics, enhanced efficiency, and life extension of facilities.

* The importance of safety, reliability, and aging were themselves driving issues.

* Reliance of old technologies:

Current nuclear power facilities are largely based on 1970's technologies. (Note that the personal computer age began in the 1980's.) Such technologies limit performance and need to be updated.

Common Barriers

A number of barriers or impediments which could inhibit development in the R&D topics were commonly identified.

* Regulations and uncertainty about changes:

The nuclear industry is tightly regulated. Changes in the operation of power plants require substantial technical justification and support. Uncertainties as to the willingness or ability of the NRC to modify the regulations sometimes inhibits an investment decision to undertake the necessary long- and short-term research.

* Database Inadequacies:

> The development of computational models can be impeded by an inadequate data base for testing and validating the model. Furthermore, the original data from older research programs have either been lost or become irretrievably degraded, and even more-recently acquired data is in danger of being lost, because the resources and means for preserving and reading them are disappearing. Also, little work is being done on reviewing them and ensuring that their integrity is maintained. Similarly, the experience gained, in the form of "corporate memory," is being lost as older experts retire without being replaced or without transferring their knowledge to those who replace them.

* Complexity of the Problem

> In some cases, the problem can be seen as sufficiency complex as to limit the ability to make fruitful developments within the appropriate time frame.

General Recommendations

The Working Group adopted two general recommendations with regards to future R&D in the topic area. These recommendations will be followed by a more detailed list of the specific topics.

1) DOE should support R&D in two broad categories:
   - Fundamental long-term science and engineering on enabling methods and technologies related to the safety, reliability, and aging of current and future reactor designs; and
   - Intermediate-term R&D related to diagnostic and monitoring methods and to regulatory support.
2) Wherever possible, DOE should ensure that the research be done with multidisciplinary coordination among all relevant DOE offices and other agencies to take advantage of the research being done there.

SPECIFIC TOPICS

Fundamental Research

A number of important research areas requiring D.O.E. support can be classified as "Fundamental Research." Advances in knowledge in these areas could lead to revolutionary advances in reactor safety, performance, and reliability. Therefore, support for research in these areas is critical. At the same time, progress in these areas requires advances in fundamental understanding and cannot be justified by the present-day nuclear power business climate. Because of the investment uncertainties, only the Government is likely to fund these far reaching research areas. The payoff in performing research in these areas is fundamentally long-term, but will provide some intermediate term benefit. The areas identified by the working group are:

* Environmental Effects on Materials:
Radiation effects, radiochemistry, corrosion, and technology for joining, including both experiment and advanced computational techniques. The radiation inherent in reactor operation creates a unique environment that can accelerate the degradation of certain reactor structural materials. Radiation effects such as loss of ductility, dimensional changes, and accelerated corrosion and cracking occur to some extent in any reactor design. Inadequate control of water chemistry can exacerbate these degradation mechanisms, as well. To ensure successful life extension in current water-cooled reactors and to improve the efficiency and economics of current and future reactor designs, a better fundamental understanding of radiation effects, radiochemistry, and corrosion in a reactor environment would be beneficial. Advances in the understanding of radiation effects would lead to improvements in plant reliability and component reliability and predictability.

> To provide materials with improved performance in a reactor environment, the development of both advanced multi-scale computational techniques and experimental programs are required. Multi-scale modeling describes the combination of very-short-time/small-dimension- scale simulations with long-time/large-dimension simulations. Successful simulations combine basic radiation-damage simulations with microstructural evolution simulations to predict macroscopic behavior such as mechanical properties or corrosion. Experimental programs are required to understand degradation mechanisms and to support and validate computational techniques. Sufficient radiation testing and analysis facilities are required to support experimental activities. Future plants need to be designed specifically to include a materials surveillance program. Joining technologies and the effects of radiation on joined components form a special category within environmental effects.
>
> To test a material's response to radiation, it must be irradiated. Accelerating the rate of irradiation can provide the correct fluence, but accelerated tests add an uncertainty in that the damage rate does not match that of actual reactor material. This limits the speed at which data can be acquired at actual reactor conditions. Therefore, research must be very forward-looking. Even for material behavior or fuel performance information needed in 10-20 years on, the experimental planning needs to begin now, so that sufficient time is available to irradiate the test materials/fuels to establish an adequate database for design evaluation and regulatory assessment.

* Fluid Mechanics:
Computational and multiphase fluid dynamics, fluid/structure interactions.

> The ability to accurately model the fluid flow and heat transfer capability of reactor coolants is vital to understanding the margins to safety in any reactor plant. Continued improvement in design-basis accident (DBA) analytical tools have already, in some cases, resulted in elimination of these events from establishing limiting conditions for normal operation (e.g., peak fuel rod power, power shape, etc.) in currently-operating water reactors. This trend is expected to continue as more utilities turn to so-called "best-estimate LOCA" codes. As a result, transient events and local thermal-hydraulic (T/H) conditions will likely establish limiting operating conditions. This is expected to

be true for future water reactor designs, as well. For other reactor types (liquid-metal or gas-cooled reactors), local T/H models are essential for analyzing core T/H performance. Improvements in smaller-scale, local thermohydraulics models (e.g., subchannel T/H models, computational fluid dynamics models) could lead to reduced conservatism and to improved economics in plant operations.

Computational and multiphase fluid dynamics techniques that accurately model fluid flow and heat transfer on all time and space scales are needed. Research is needed to improve both multiphase and single-phase fluid dynamics models. These techniques would range from small-scale simulations of localized effects such as boiling to large-scale full plant simulations.
The simulations also need to correctly model the coupling of the different scales in normal, transient, and accident conditions. Experimental work to support and validate computational techniques is also required. An example would be obtaining heat transfer data on supercritical liquids for advanced high temperature reactor designs. Additionally, experimental programs to provide improved knowledge of fluid/structure interactions will lead to improvements in plant reliability and component reliability and predictability. In addition to improved analytical techniques,methods that improve the ability of regulatory bodies to respond to new technologies would quicken the acceptance of these new technologies.

* Fracture Mechanics and Fatigue:
Experiment and multi-scale modeling.

Improved mechanical reliability and performance is critical to increased component lifetime, leading to improved economic performance. To increase service life, reactor components need adequate strength and ductility and the ability to withstand fracture. To meet this goal an improved understanding of crack propagation in an irradiation environment is required. The study of fracture mechanics, both experimental and multi-scale modeling is necessary to better understand and predict component performance. Another important area for fracture mechanics research is to find methods to incorporate probabilistic predictions into codes, so that the NRC can use them as it makes the transition to risk-informed regulation.

Thermal striping (rapid-thermal-cycle-induced fatigue) of plant components has recently caused cracking and failure of piping in operating plants in Japan and France . One of the fundamental limitations in understanding thermal striping is calculating the rapidly changing fluid temperature at the material surface. Limitations of both the single-phase computational fluid dynamics turbulence models in handling simultaneous momentum transport and energy transport and of the ability to calculate the behavior of the structure being thermally striped prevent understanding and prediction of material's performance.

* Intelligent Materials:
A huge improvement in performance safety and reliability could be achieved by developing materials that can sense, respond, and/or change properties in response to the radiation environment. These capabilities would revolutionize materials performance.

Diagnostic and monitoring methods, regulatory support

A second major grouping of required research involves research areas that primarily relate to current plants, but would also provide benefit to any future plant. These group includes topics such as: developing reliable models and codes to reduce the uncertainties in safety and reliability issues; providing methods for DOE and NRC to work together in developing research-based data and information on licensing issues, without compromising the NRC independence; making regulations
amenable to future designs and innovations, and developing a research base to support license approval for specific DOE missions. Specific research areas include:

* Digital Systems Instrumentation and Control:
Signal diagnostics and analysis, in-situ performance monitoring, failure prediction.

> Improving the ability to sense component and system performance parameters, reducing the uncertainty in performance parameters, improving the information obtained from sensed signals, and improving the ability for operators to interpret the meaning of signals would all improve plant reliability and performance. Reducing the uncertainties associated with data that supports a safety analysis would increase the efficiency by reducing unnecessary shutdowns. The ability to predict which components need replacing prior to plant shutdown (instead of during the shutdown) would save much time and resources.

* Virtual Knowledge Management:
Knowledge management needs fall into two basic categories: 1) the ability to access larger quantities of data while intelligently processing and managing this data to provide the operator with the optimum data stream, and 2) the ability to retain and transmit a knowledge base developed over years of plant operation to future generations of plant designers and operators. Knowledge management systems may be prohibitively expensive to retrofit into current plants, but would be valuable to future plant design.

* Plant Modeling and Simulation:

Plant performance, safety, and economic performance could be improved by developing a system that could provide predictions of individual component performance and integrated plant operations. These models need to be able to handle uncertainty analysis and provide accurate assessments of safety margins.

* Remote Technologies:

The ability to remotely monitor, operate, and repair components will increase safety by reducing radiation dose to employees and also improve economics by reducing the number of employees needed. Research into remote and robotic systems is required to provide these capabilities.

* Risk Informed Regulation Support:

Reactor plants can improve their economic performance by operating within a risk informed regulatory structure. Because this structure is fundamentally different from traditional regulatory practice, research will need to be done to improve the ability to define and quantify the risk associated regulatory imposed requirements. Weaknesses in the current technology database feeding probabilistic risk analysis must be addressed. Examples are human performance modeling, probabilistic risk analysis, common cause failures, and non-loss of coolant accident transient analysis.

* Regulatory Support for DOE programs:
Tritium production, MOX fuel

> Certain DOE missions such as tritium production and MOX fuel production require research to provide a basis for the regulatory system. Because these projects are unique to DOE, DOE will need to do the research necessary to support the projects.

Appendix G

Working Group Report on – Advanced Instrumentation/Controls/Simulation/ Operational Aspects

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Instrumentation and Controls/Simulation/Human Factors Working Group
December 8-10, 1999 Workshop

Instrumentation and Controls/Simulation/Human Factors

Summary Report

December 8-10, 1999

Working Group Participants:

Steven Arndt -, Nuclear Regulatory Commission
Dennis Berry, Sandia National Laboratory
Mark Bryden, Iowa State University
Doug Chapin, MPR Associates
Beverly Hartline, Los Alamos National Laboratory, Breakout Group Leader
Carolyn Heising, DOE-NE and Iowa State University
John Lee, University of Michigan
Marty Martinez, Jupiter Corporation
John O'Hara, Brookhaven National Laboratory
Ted Quinn, MDM
Mark Strauch, Lawrence Livermore National Laboratory
Dave Weber, Argonne National Laboratory
James White, Oak Ridge National Laboratory[*]

I. Summary

The breakout group was charged to identify and recommend R&D needed to enable the use of advanced instrumentation and control (I&C), simulation capability, and virtual reality in the design, construction, and operation of nuclear power plants over the next 20 years. The group was to identify both human factors (including interface issues) as well as technical issues associated with these technologies. In addition, we were asked to provide advice on the appropriate role for the DOE and NE in the effort.

These rapidly advancing technologies offer enormous potential for improving the safety, reliability, proliferation-resistance, and economics of nuclear power. Benefits should accrue to the current fleet of plants as well as to Generation III and IV. With the new knowledge, capability, and advanced technologies that should result from the recommended research, it is conceivable that eventually nuclear power plant control rooms could have many "Star Trek Bridge" features, with operations and maintenance supported by high-fidelity, real-time simulations and accurate measurement of all parameters of interest.

However, nuclear power is a conservative, capital-intensive, and safety-regulated industry. The inherent time scale of product development and obsolescence in digital-based technology and instrumentation (~18 months) is very short compared with the multi-decade lifetime and investment-recovery period characteristic of a nuclear plant. How to mesh these time frames, adapt/develop devices and simulation models to nuclear-plant requirements, achieve demonstrable fail-safe performance from systems built using these technologies, guide updating of the regulatory framework and licensing criteria, and attract talented people are among the

---

[*] Unable to attend, sent contributions

challenges the suggested R&D addresses. It is encouraging that the Nuclear Regulatory Commission is currently receptive to improving the regulatory framework without compromising public health and safety.

Several important long-term research topics are identified and summarized in this report. There are many overlaps and interfaces between the recommendations and conclusions of this breakout group and the others at the workshop. Thus, we urge DOE, other sponsors, and proposers to integrate advanced I&C, simulation, and human-factors aspects into research programs and projects focused on the subjects addressed by other breakout groups at this workshop. We present the R&D recommendations in six major areas:

- **Crosscutting Issues**: regulatory-related research; R&D supporting technical standards, hardware interfaces, and reconciling the mismatch in time scales between nuclear plants (decades) and digital technologies (~18 months); advanced R&D infrastructure; and education and training.
- **Advanced-Instrumentation** research to adapt, develop, and/or validate: robust communications; wireless, high-accuracy, inferential, radiation-hardened, micro-analytical, and 'smart' sensors and devices; signal handling; condition monitoring; and the use of commercial, off-the-shelf equipment.
- **Controls and Control-Room** R&D to enable: fully integrated control rooms; adaptive automation; advanced diagnostics and control algorithms; better informed operator decision making; and safe operation of 'hybrid' I&C systems as existing plants replace analog with digital technologies in a phased manner.
- **Operations and Maintenance** research to advance: condition-adaptive maintenance and operations; on-line monitoring and robotic maintenance; virtual reality and simulation support for maintenance planning and operations; and 'self-healing' systems.
- **Modeling and Simulation** research to develop and confirm: high-fidelity, integrated, phenomenological, multi-physics, large-scale, and/or virtual-reality computer models; real-time simulation tools; and statistical models for component reliability.
- **Human-Factors and Human-Machine Interface** studies to guide the design of effective human-system interfaces (HSI) and to advance the fundamental knowledge base on human factors relevant to nuclear plant operation, maintenance, and training. DOE-NE has a role in future R&D related to the I&C/Simulation/VR/Human Factors areas.

Priority should be placed on topics and projects with the greatest potential to save money or solve a problem while maintaining safety and reliability. DOE's role should be to catalyze partnerships and collaborations (including international ones) and to sponsor or cosponsor R&D with significant societal benefits that won't happen without government involvement, due to risk, long-time horizon, or inadequate economic benefit for a commercial sponsor. A very important role is to fund (or cofund) the development of software, facilities, and knowledge that should be available to and shared by all stakeholders, rather than held on a proprietary basis for the economic benefit of its owner.

This report first proposes a long-term goal and vision for nuclear-energy-related R&D on instrumentation, controls, simulation, and operations. It then discusses the context and barriers for the R&D and the use of these advanced technologies in NPPs. The largest section describes several example R&D topics and subtopics that emerged in the working group's discussions and brainstorming. The final section addresses the niche for DOE in these efforts. The topics described are representative of promising research, but do not intend to be a complete listing. This report provides a basis for discussion and will be used as one of many sources for a long-range R&D plan being developed under the auspices of the Department of Energy's (DOE) Nuclear Energy Research Advisory Committee.

II. Goal/Vision

Information technology, sensors, instrumentation, communications, simulation, numerical models, and information management and display are advancing rapidly and offer a potential for adoption and/or adaptation for use in nuclear power plants (NPP). The long-term goal for NPP-related R&D on these technologies is to improve the safety, reliability, and cost-effectiveness of the plants. The R&D effort proposed by the working group is sufficiently broad that benefits should accrue in plant design, construction, operation, maintenance, and decommissioning. It includes parallel attention to the regulatory framework and process along with advances that will evolutionarily or revolutionarily change the role and training of operators and their physical and behavioral interface with the plant. R&D and implementation of these fast-moving, state-of-the-art technologies, moreover, are likely to attract bright young people to careers in nuclear power.

Sample elements of our vision for the role of computer technologies, digital instrumentation, controls, advanced simulation, and human-factors knowledge in NPPs in 2020 include the following:

- ‘Star-Trek bridge’ control rooms with natural human interface and extensive automation;
- ‘Smart’ and self-healing sensors, components, and subsystems enabling robust, inherently validated operations and monitoring;
- High-fidelity and real-time simulations and virtual reality to support design, operations, training, and maintenance;
- A new regulatory environment that ensures safety yet meshes with the innovation time scale inherent in high technology;
- A ‘learning system’ in which the people, technologies, and the information systems associated with nuclear power continually expand their capacity for safe, reliable, and cost-effective operations; and,
- R&D on any NPP topic routinely includes appropriate efforts on instrumentation, controls, simulation, operations, maintenance, and human-factors.

The R&D program to achieve the vision includes synergistic and coordinated efforts sponsored by DOE, industry, and international or foreign organizations. The R&D would:

- Focus on Generation II, Generation III, and Generation IV NPPs, thereby promoting both retrofittable and revolutionary advances;
- Leverage the considerable industrial, Federal, and international investment in fast-moving information technologies and instrumentation;

- Develop an updated regulatory framework and the technical data needed to support it, that would reduce the time and cost of obtaining initial regulatory approval for innovations in these areas;
- Include human-factors R&D to establish the knowledge base needed to advance operations, maintenance, training, qualification, and the control room; and,
- Build, integrate, and validate simulation codes and reactor-systems and physics models to support applications ranging from real-time decisionmaking to physically detailed, extremely high-fidelity simulations.

Section IV presents the R&D topics and subtopics recommended during the working group meeting. This presentation makes no assumptions about who should sponsor or perform any particular research. We urge that the R&D portfolios of the various players (DOE, other Federal agencies, industry, international and foreign organizations) be well coordinated, and that as much as practical the performers and projects be selected using a merit-based, competitive review process. In Section V we discuss our view of the appropriate role of DOE as a key research sponsor.

III. Context: Drivers and Barriers

R&D to provide and apply advanced instrumentation, controls, simulations, and human-factors knowledge to NPP is driven primarily by the very significant potential of these technologies to increase safety and reliability and lower construction and operations costs. Many hundreds of billions of dollars per year are invested by industry and government in the underlying information and sensor technologies. These investments are producing ever-more capable, inexpensive, fast, and reliable devices and ways to use them.

- Nuclear-specific aspects of the advanced information and sensor technologies, such as fail-safe components and architectures and radiation hardness, can be pursued and demonstrated comparatively cost effectively, building on the fast-moving technology base.
- Computer hardware, software, and information processing are sufficiently capable now to offer real advantages to NPPs. Faster and more powerful computers and more faithful and complete simulation codes would provide opportunities for calculations that are fast enough to support plant operations in real time and to improve their design, modeling, and licensing basis. Qualifying the codes and simulations through the regulatory process might not be as straightforward, however.
- The Nuclear Regulatory Commission (NRC) today is unusually receptive to developing new improved ways of doing business.
- With more detailed, timely, and accurate measurements of plant performance, operations and maintenance could be more solid and fact-based.
- The use of computers, thoroughly validated simulation codes, and sophisticated databases could help ensure that the experience and wisdom learned across the industry and throughout a plant’s life would be available in real time to support design, operations, maintenance, and decommissioning decisions.
- The field of human-factors research is sufficiently mature that systematic understanding of the role and behavior of people in normal and emergency situations can be developed and applied.

However, nuclear power is a capital-intensive and safety-regulated industry in an economically newly deregulated business environment. The inherent time-scale of product development and obsolescence in computer technology and instrumentation is very short (order of 18 months or less). Yet the recovery period for the very substantial capital investment in an NPP and the plant's planned lifetime are very long (order of several decades). In this context, several barriers and conflicts emerge:

- The tension is considerable between the need for robust, maintainable standardized components and the opportunities to improve performance by utilizing rapidly advancing, state-of-the-art devices. How would one maintain a plant when component manufacturers continuously replace their product lines with new, 'upgraded' models?
- The conservative regulatory environment imposes a large burden to qualify components and plant changes, with the typical licensing time likely to be longer than a particular model of a digital component that might be available. A regulatory framework that truly assures safety while qualifying new technologies, configurations, and components as rapidly as they emerge in the electronics industry would be extremely difficult.
- Digital technologies do not yet have the reputation for fail-safe performance demanded of any NPP overall, and its systems, subsystems, and components separately.
- To do the necessary R&D and to implement the resulting improvements will require recruiting bright, talented people with expertise in these fast-moving fields. Such people already have a broad range of exciting and lucrative career prospects.

IV. Priority R&D Topics

For the purposes of identifying promising R&D topics and subtopics, the Breakout Group has organized this section into six major areas, where research would resolve key issues, develop the needed knowledge base, or make the adaptations required for the nuclear-plant environment. In fact, there is a lot of overlap and interaction between and among these areas. It was hard to sort the topics uniquely into the six areas, and many research projects that might be proposed would fit into more than one area. The R&D areas used for structuring this report are:

- Crosscutting Issues
- Advanced Instrumentation
- Controls and Control Rooms
- Operations and Maintenance
- Modeling and Simulation
- Human Factors and Human-Machine Interface

Cross-cutting Issues

In the breakout group discussions, after brainstorming R&D needs in each of the five technical topic areas, we considered whether important research would be missing because it either overarches or falls between the chosen categories. The answer was 'yes:' regulatory issues, standards, R&D infrastructure needs, and human-resource issues. This section mentions these 'orphans.'

1.) Regulatory –Related R&D

The legal framework captured in US NRC and industry codes and standards that govern many of the details of nuclear power design, construction, and modification was developed as the industry was developing and fielding the Generation I and early Generation II reactors. The technical basis comes from the collective wisdom and experience of the engineering and scientific community, heavily weighted toward what was known at that time. Design margins (e.g. cable sizes, levels of redundancy, piping thickness, and so on) are often quite prescriptive and not easily changed. Most of the general regulatory principles, such as the single-failure criteria, as well as the specific regulations, were developed long before the advancements that high-speed digital electronics would bring to modern I&C were known. Although a promising new technology (e.g. an addressed condition-monitoring sensor or an analysis code) may justify a reduction in a design margin, the reduction cannot be implemented until it is incorporated in the governing codes, standards, and regulations. R&D needs to be conducted to determine: (1) where today's codes and standards prevent the use of advanced I & C/simulation/operations, (2) how they could be changed to be more applicable to digital I&C without compromising plant or public safety, (3) how the regulatory framework of the future should be configured to facilitate the adoption of rapidly advancing technologies, while continuing to assure safety, and (4) the technical information and metrics needed to permit regulatory acceptance of these new technologies.

In addition, research is needed to ensure that methods for regulatory validation and approval of new technologies are available by the time the technology is ready to be considered for licensing. Another effort should establish the knowledge base for an appropriate new benchmark or set of regulatory approval criteria for Generation IV plants. For instance, the accident analysis would not be the same for Generation IV as for the earlier generations because the transient response in Generation IV is a lot slower.

Research is also needed to guide the regulatory approach to hybrid control systems that will be in place when current plants upgrade from analog to digital systems in a phased manner over many years. The current sets of regulations are essentially in either of two forms: an older set based largely on analog equipment and a more recent set based primarily on digital technology. Hence, regulatory guidance is available for either part of the hybrid system but not for how to ensure safety when a plant's I&C system makes extensive and transitional use of both types of technology.

2.) Technical Standards and Standardized Interfaces

The ability to infuse new technology and avoid the burdens of obsolete systems will be enhanced through the appropriate development/selection of technical standards and the development and adoption of versatile standardized interfaces. This need is exemplified, for example, by an anticipated evolution of sensors from the simple types supported by 4-20 mA serial loops to sophisticated devices with embedded computing running Java applets requiring a web-based interface over an ethernet connection. In many cases the standards and interfaces are implemented in the device industry, which serves many different applications. Research is required to identify existing and emerging standards that will materially impact future standard interfaces for NPP instrument and control systems, and to provide the knowledge base needed to participate in standards adoption and ensure they would be nuclear compatible.

3.) Reconciling the Inherently Different Timescales of Nuclear Power Plants and Modern Digital I&C Systems

As a result of the large mismatch between the timescales of NPP life times and digital technology evolution, it could easily be that the systems designed for use in a plant would be obsolete and in danger of reduced or abandoned vendor support before the plant is even operated. Certainly electronic devices and computers will go through many generations providing many-fold increases in performance during the life of a plant. Problems created in this environment include: loss of vendor support (spare parts and technical support and training, etc); increased cost to either maintain your own systems independent of the vendor or to keep changing out equipment as the vendor upgrades; undesirable and (and risk increasing) creeping functionalism as more features are added to the vendor's standard I&C systems which might not be needed in the plant; design-basis changes; and, licensing and training of operators and maintenance staff. It is unrealistic to expect that the nuclear industry will drive the I&C industry to match nuclear life cycles. Hence, an effective strategy must be created to deal with this fundamental mismatch in time scales. Research is needed to investigate various strategies and technologies to address this issue. Some topics will be hardware or software oriented, such as picking technologies, which can be easily replicated, or controlled or preparing the software and documenting it in a readily available form (*e.g*. the customer obtains and controls the original software for the system). Other research is more administrative in focus (*e.g*. to define how the plant design basis and regulatory guidance can be kept current more readily so that regulatory oversight can be effective but not act as an overly restrictive drag on the process).

4.) R&D Infrastructure

The R&D programs being proposed focus on reactor concepts that require a better understanding of identifiable physical phenomenology as well as understanding of new phenomenology present in alternative reactor designs. To be accepted by the public and licensing authorities, the critical concepts and phenomenology must be demonstrated both analytically/computationally and experimentally. Consequently, adequate experimental infrastructure must be developed to verify phenomenological and modeling predictions, to insure the correctness and adequacy of proposed designs and operating conditions, to contribute to the licensing basis, and to test new concepts in a safe, flexible, and extremely well monitored setting. The purpose of the research would be to identify infrastructure needs for the proposed research, then to construct and operate these experimental facilities. One attractive candidate would be a research center for advanced control room, human-system interface (HSI), and I&C technology development. Another one is a virtual-reality facility capable of simulating a plant or pilot plant with fully interactive, three-dimensional interfaces. In addition, university research reactors (URR) could be used to study many of the issues associated with incorporating digital I&C in NPPs. Although their I&C systems are comparatively simple, URR provide an environment complicated by the real-world problems of regulatory constraints and radiation. Thus, URR are attractive facilities for studying advanced control algorithms, HSI issues, on-line monitoring and diagnostic systems, and advanced instrumentation and sensors.

5.) Education and Training

The advanced R&D plan being developed by DOE/NE is focused on use of state-of-the-art and leading-edge technology for nuclear power plant design, analysis, operation and maintenance.

Clearly, to take advantage of rapid advances in instrumentation, sensors, materials, control, and simulation capability for the benefit of nuclear power, nuclear engineers, regulators, and plant operators will require specialized skills and knowledge beyond the traditional. In most of these areas, the nuclear-energy industry will be competing with other industrial and commercial segments for qualified talent. To realize the technical objectives will require attracting very talented young engineers and scientists. In addition, the technical capabilities of current researchers will have to keep pace with the state of the art. The objective of this research area is to identify and develop innovative and effective pedagogical approaches and instructional materials. Thus, the needed advances in education and training will be available to prepare personnel qualified to lead and support the research programs proposed here. Although it is not a research topic, in itself, human-resource recruitment and development is an important challenge in its own right, and will need attention.

Advanced Instrumentation

The broad topic of advanced instrumentation includes devices, sensors, along with means to communicate with them, maintain and replace them, and verify and use their information to support plant operations and maintenance. Many have been and are being developed for and used in other applications. The generic issues that need to be addressed for nuclear power plant applications include:

- The impact of these devices on nuclear safety, specifically their reliability, the need for redundancy, testing and certification of smart devices and embedded software, and the effects of radiation on the devices;
- Identification of specific applications where these devices have the potential for a significant positive impact on current problems, or could significantly improve plant operations;
- The development of standards and methods for nuclear certification of these types of components; and,
- How to verify and calibrate their signals *in situ.*

1.) Robust Communications and Wireless Sensors

Advanced instrumentation and control systems in power plants will be based on the use of large, integrated, distributed digital systems with many more and more advanced sensors and other nodes than present systems. For example, increased use of sensors will be of interest to provide extensive capability for condition assessment in components and equipment throughout the plant. Robust communication throughout the network will be crucial. Present systems employ physical cables to carry the signals and distribute power for monitoring and control functions. These cable systems are expensive to install, are subject to aging over long periods, and provide a vulnerability to common mode failures. Future plants will require a robust communication system that is easier and much less costly to install but still provides the necessary isolation and segregation of signals. Current plants are beginning to use optical fiber and some exploration of various wireless communication networks is being done. Research and development is needed to define and make practical a robust communication system to support advanced instrumentation control system applications in a power plant environment with its physical boundaries and structures, large metallic structures, varying electromagnetic fields and potential transients due to switching transients in power equipment and from external effects such as lightning. Current advanced digital I&C equipment available are already capable of producing signals that can produce upsets in other equipment (e.g., walkie-talkie signals can trigger undesired response in digital electronic equipment) and have susceptibilities to interfering signals from other equipment either through radiated or conductive paths. Operational restrictions, special shielded enclosures, and filters are needed to deal with these problems. The needed research program would identify potential robust communication techniques and architectures which could be used with high confidence in nuclear power plant applications to support large scale, integrated, distributed digital I&C systems which do not require the use of cabling for communication. R&D is needed to understand the performance and reliability of wireless systems under normal and accident conditions. These conditions include ambient EMI/RFI, harsh conditions that may degrade link bandwidth (e.g., steam, water, radiation) and susceptibility to unintentional/ intentional interference (e.g., maintenance crew transmitters and sabotage).

2.) Instrumentation for High-Accuracy Measurement

Instrumentation providing measurements of a higher accuracy than currently available is needed for some applications. One example is the need to measure water level more accurately than is currently possible. Another example would be to monitor neutron flux in a way that adjusts for temperature changes, boron concentration, and types of shadowing. This new instrumentation would have to be able to meet the qualification requirements for the Generation IV environments and safety classification.

3.) Inferential Sensing and Virtual Measurement

Instrumentation to measure a parameter directly often cannot be placed at the point of interest. Therefore, devices should be developed that compensate for the difference between the installed location of the instrument and the point of interest of the parameter or measure related parameters and accurately infer the parameter of interest. An example of such inferential sensing may be to use temperature to measure level (heated thermocouple is a current example) or accounting for the difference between an resistance temperature detector (RTD) located on the surface of a pipe and the measurement of the temperature at the center of flow in the pipe. This R&D may include the development of algorithms for processing signals from multiple sensors in several locations.

4.) Radiation Hardened Sensors

As sensors become more sophisticated (e.g., embedded electronics, micro-electro-mechanical systems (MEMS) structures) the need to understand the performance of such sensors in high radiation environments will increase. Conversely, the known radiation performance of certain materials may influence their inclusion in advanced sensor development. R&D should focus on material selection and device/structure integration to achieve high overall performance (accuracy, lifetime, etc) in a high radiation environment. Integration includes process-development research to enhance radiation resistance of assembled devices/structures/components.

5.) Use of Commercial Off-the-Shelf (COTS) Equipment

Much of the I&C equipment in current nuclear plants is custom hardware. This equipment is expensive to purchase initially, is expensive to maintain and introduces special burdens with custom training and maintenance activities. Further, since nuclear is a very small market, the vendors tend to quickly lose interest in supporting this equipment. The commercial I&C market is huge and will follow its own directions so it will be imperative that nuclear plants be able to effectively use COTS equipment in their I&C systems. Utilization of COTS equipment will avoid becoming orphaned quickly, will take advantages of standard maintenance and support technologies, and will ease the problem of ongoing upgrades. Work is currently beginning on how to qualify COTS equipment for use in nuclear plants and the initial results indicate costs are still very high, and each application tends to be a custom assessment and a case-by-case qualification. R&D is needed to identify more clearly the critical attributes needed in COTS equipment to enable its use in nuclear applications, provide standardized techniques for carrying out the needed assessments, defining effective ways to supplement COTS design and testing approaches to meet nuclear standards, and working with the vendors and manufacturing groups to investigate whether relatively minor changes could be made in current commercial products and processes to support their use in nuclear service. For example, by coordinating efforts with other users of safety critical systems, such as the petrochemical industry, the military and the aerospace industry, a large enough market could be defined for common features which would make the use of COTS equipment easier and much more cost effective for all of the parties.

6.) Signal Handling

The assessment of plant status depends on an accurate measurement of actual plant conditions, normally provided by sensors in the plant instrumentation system. Such information is used to guide operator actions. When advanced control room, decision-making aides are available, some signals must couple into those aides and could be used to set status conditions and initial conditions for predicting system behavior and real-time 'what-if' analysis. The objective of this research is to develop techniques and software that can assure the operator and/or control system that the reported signals reflect actual plant conditions (on-line signal verification and validation). Additional studies would develop techniques that allow coupling of sensor signals to use as inputs for simulations that assist the operators. (See R&D topics in the simulation section). Such techniques should determine the consistency of multiple sources of related information, identify faulty sensor information, provide highest confidence initial conditions, account for uncertainties and fluctuations in the signals, and establish system and component status for use in the subsequent simulations. The transient management and control software should be designed so that unanticipated events and, to the extent possible, accidents of unknown nature could be properly handled so that the plant can be maneuvered to a safe operating condition or shutdown state. Development of software with these attributes will require advanced diagnostics and control (D&C) algorithms together with accurate simulation models that may offer both symptom-and function-based diagnostic information.

7.) Condition Monitoring

Many industries and industrial sectors are benefiting from advanced condition-monitoring technology, especially when conditioning-monitoring information is tracked and analyzed by reliability, safety, or maintenance software. Through the use of Smart Sensor signals, historical data, system-response models, and probability-analysis techniques, nuclear power plant operators and regulators can make more technically grounded decisions regarding maintenance schedules, safety margins, the need for unscheduled outages, and hardware upgrades. Furthermore, longer-term concerns (e.g. aging) and accident response options (e.g. equipment operability following a fire or earthquake) can be addressed through well-correlated and enhanced condition monitoring.

One of the technologies for condition monitoring takes advantage of a robust suite of imbedded sensor techniques that could be developed or adapted. Advanced microelectronics now enables the development and use of imbedded sensors in many locations here-to-fore not possible. These applications and locators include: strain measurements of structures and piping; corrosion of material; localized temperature, flow, pressure, and vibrational conditions; and localized electrical properties, among others. R&D topics range from the development and demonstration of embedded sensors and other technologies to issues associated with sensor powering, communicating, and integration over what may be a 60-year emplacement. Condition monitoring R&D topics include specific pH, insulation resistance, structural stress levels, and software and techniques for data integration and failure prediction.

8.) Micro Analytical Devices

Micro analytical devices are being developed that will provide low cost, highly reliable measurement of temperature, pressure, gas species, and other parameters. Because of the small size and low cost, these devices will be used for the development of smart components, and control systems based on real time analysis. It is likely within 5 to 10 years that these devices will link with the hardware (pumps, pipes, valves) in control and analysis systems and allow real-time analysis, predictive maintenance, and operator assisted control. Industries that are currently developing these types of devices include the automobile and the non-nuclear power industry. The R&D issues that need to be addressed for nuclear power plant applications include primarily the generic issues identified in the introduction to this section.

9.) Smart Instrumentation and Equipment

Today smart instrumentation and equipment typically are ordinary devices linked to an artificially intelligent control system. The smart systems of the future are likely to be significantly different. The smart plant will be built from smart components that provide a wide range of information and analysis to an analysis and control system. This analysis and control system will perform complete systems analysis, across multiple scales and systems utilizing real time, high fidelity, computational models to explore and find the optimum path for operation of the plant. This optimum will include a wide range of concerns (e.g. safety, ease of operation, efficiency, and cost). The goal of R&D would be to develop and qualify smart instrumentation and equipment for use in current and future NPPs. Smart instrumentation would be like "watchstanders," monitoring NPP components and systems. The key characteristics of a smart component include measurement and analysis of one or more parameters and decision making and action taking (e.g. forwarding the results for consideration by a larger system, taking the independent action, logging the results for future consideration, etc.)

Controls and Control Rooms

When NPPs were first developed, the challenge of controlling these enormous, complex, and hazardous systems led to the development of control systems and control rooms that defined the state-of-the-art. Since then, NPP control has remained reliant on the licensed, approved control concepts and hardware, which represent 1950s/60s technology and knowledge. Needless to say, breathtaking advances in computer hardware, software, control concepts, etc. have taken place in the intervening decades, to the advantage of manufacturing processes in many industries and for the control and operation of other power plants and a variety of large, complicated systems. Key among the generic R&D issues prerequisite to full use of the rapidly advancing information technology capability are the regulatory framework and associated standards (see Crosscutting R&D).

Controls and control rooms must link with plant-monitoring instrumentation, utilize models and simulations, and provide the interface to the operators. Thus, many R&D topics in the sections on instrumentation, simulation, and human factors are also relevant here, and *vice versa*.

1.) Fully-Integrated Control Room (aka: Star Trek Bridge)

Future nuclear power plants may be less-complicated and more forgiving (i.e. inherently safe), and it is reasonable to expect that new control rooms will evolve to help simplify operator decisions and actions through automation, expert systems, condition monitoring, accident assessment, decision support software, and “man-machine” interfaces (e.g. GUI’s). At one end of the spectrum is the control room of today, with many different gauges, switches, meters, and controls that an operator learns to deal with. At the other end of the spectrum is a nearly featureless control room that more or less runs entirely on autopilot without any significant operator action required. However, it is not clear what the optimum control room should look like and how it should interface with operators. There are many opportunities for innovation, especially if a 10- to 20-year horizon is considered. Research should support the development of a control room providing a fully integrated information and control system. The control room would break away from the tradition of separate human-system-interface (HSI) resources for alarms, information, procedures, support systems, and controls. Instead, these systems’ functions will be integrated into an HSI supporting plant monitoring, detection of disturbances, situation assessment, response planning, and response execution by a combination of crew members, intelligent agents, and automatic systems. The goal of the research will be to develop an interface between plant and personnel, that provides information to the crew in a way that operators get information effortlessly, when and where they need it, and in an immediately understandable format. The interface will provide error tolerance, i.e., minimize human error and provide a means to detect and recover from errors when they do occur. R&D topics could explore the feasibility and benefits of voice commands/ questions, database management, and automated action without human involvement, while addressing issues of safety, reliability, and human factors.

2.) Real-time Analysis to Support Operator Decision Making

Currently all operations in NPPs are, in part, human-in-the-loop operations. This situation is similar to many activities, e.g., driving a car, in which human intervention and decision making are key components of safe operation. The key difference that will be developed in many industries during the next 10 years is that these human decisions will become more informed. Instead of reading a pressure, flow rate, and temperature and deciding on the course of action, the operator will have available a wide range of analysis and real-time simulation tools to aid these decisions. "Real-time" refers to analysis that enables the operator to ask questions/perform analysis and receive the results without delay, that is in real-time (~1-10 seconds). These systems will extend beyond artificially intelligent and neural net approaches and will be based on the fundamental physics of the systems involved. They will include the impact of coupling multiple scales and multiple systems together to predict unforeseen events, and to explore the full range of possible operational paths available. Plant simulators already are designed to provide a predictive capability of the system, given a set of initial conditions, a sequence of operator actions, and the evolution of individual systems and components. If such simulators were to become capable of predicting system behavior under a broad spectrum of scenarios and if they are able to run in real time and/or faster than real time, they offer the opportunity of being a decision aid to operators to supplement normal procedures and augment procedures under off-normal and unusual accident conditions. One objective of this research is to develop real-time simulation and analysis capability that can accept plant condition information as initial conditions and provide real time/faster than real time prediction of system behavior under hypothetical operator actions and expected system response. Techniques for simulator software verification and validation should be addressed. Humans would still be making key decisions, but they would be better informed than is possible at present.

3.) Digital System Reliability, Fluctuations, and Failed Sensors

The technology and methods to improve how we measure and assure reliability of digital systems (both software and hardware and how they interact) when used in nuclear power applications, are of critical importance to the continued application of these systems in NPPs. The current regulatory structure requires that new systems that are introduced into NPPs undergo an extensive and very expensive review by the NRC unless it can be shown that they do not introduce any unresolved safety issue or new failure modes. The current state-of-the-art in digital systems (both software and hardware and how they interact) is not at the level that clear predictions of system reliability can be developed for safety applications with any level of certainty. Because of this limitation the use of digital systems has been greatly limited in the NPPs in the United States (mostly in support systems).

Additionally, the lack of an effective way to measure reliability of digital systems in nuclear applications introduces significant uncertainty into the analysis of these systems in a Probabilistic Risk Assessment (PRA). This uncertainty associated with the lack of models requires that additional margin and redundancy be included into the design of these systems for NPP applications. Because the issues associated with obsolescence, slow wearing out of original I&C equipment, and the potential improvement in capability and reliability of new digital systems, it is imperative that the research into the measurement of digital system reliability be carried out, and that the particular issues associated with nuclear application of the technology, be included in this research.

4.) Distributed (remote) Computing, Control & Monitoring

Classic I&C Systems employ distributed sensors of, at best, modest intelligence arriving to a central control and monitoring point. Future systems will deploy much more advanced sensors embedding substantial computational capabilities. Such capabilities give rise to the ability to distribute, possibility in real time, the computations required to affect control. In addition, the exercise of control can be similarly distributed, and may pose interesting situations and possibilities. Experts can be consulted remotely for unusual situations. Expert teams may control multiple plants. Very highly qualified crisis teams may assume control (remotely) from steady state operation teams in time of need, for example. Remote monitoring may contribute to increased transparency of operations, especially to advance non-proliferation objectives. Research is needed to identify and solve NPP specific issues related to distributed computing, control and monitoring. These include, for example, reliability of self-forming networks of intelligent sensors and computers under failure and accident conditions. Embedding/distributing control algorithms and ensuring that real time control objectives are met, especially over the span of NPP operations, represent significant research opportunities.

5.) Adaptive Automation

The proper mix of human involvement and automatic systems will help ensure overall human-system efficiency and reliability. This research will use the fundamental knowledge developed addressing automation to support the research into the design of better integration of personnel and automatic systems by addressing the problems associated with having operators “out-of-the-loop.” These problems include operator loss of vigilance, extreme workload when automation systems fail, and loss of skill in performing control tasks. Such a system may provide for variation in the degree of automation and manual control to best achieve overall human involvement and performance.

6.) Advanced Diagnostics and Control Algorithms

In the control room for future NPPs, advanced software for D&C maneuvers will play a major role together with other features that will provide an efficient and error-free human-machine interface. The D&C software should incorporate, in an integrated framework, artificial intelligence (AI) approaches, including artificial neural network (ANN), fuzzy logic, and expert system, for diagnosis of transient events and monitoring of incipient component failures. Although these tools have been used in a variety of diagnostic applications separately, significant development and optimization effort will be required to integrate them so that key features of the AI approaches can be capitalized to yield a synthesized diagnosis. Likewise, ANN and fuzzy logic have been used individually in control studies, but little effort has been made to date to integrate these AI approaches with modern control theory algorithms in a synergistic manner. In particular, recent advances made in model-based control theory, in particular, *H-inf* control theory, should be considered. The *H-inf* ? control algorithms provide robust, stable control maneuvers and can effectively account for uncertainties in system models and at the same time reflect the desirable system performance in an integrated fashion.

7.) Hybrid Systems

There are approximately 100 nuclear plants in operation in the US. These plants were designed more that twenty years ago, and even the most modern ones do not make extensive use of up-to-date digital I&C systems. Furthermore, these plants are valuable assets to their owners, who optimize their economics by operating them for long periods (18 to 24 months) with short shutdowns (3 to 4 weeks). Upgrade of these plants to modern digital systems will certainly take place as the plants continue to age. Given the cost of the upgrade, the degree to which the I&C systems are intertwined in the plant, and the short windows of opportunity to do the upgrade work, the change-outs will take place gradually. As a result, the plants will operate with hybrid systems that are a mixture of up-to-date digital technology and older technologies. Research is needed to understand how to design and phase the upgrades and to provide the knowledge base needed to operate and maintain hybrid installations safely.

Operations and Maintenance

Effective operations and maintenance are major drivers for the safety, reliability, and economics of nuclear power. The supreme importance of safety demands very conservative operations and maintenance practices. Research should enable the development of a risk-informed approach to maintenance planning. The ability to calculate risk in real-time on the basis of known, accurately determined plant and component condition would provide a useful guide for plant-wide maintenance activities. Furthermore, simulation capability and/or virtual reality could help in the development of operations and maintenance procedures and provide training. Please see also several R&D topics described in the instrumentation section.

1.) Condition-Adaptive Maintenance and Operations (CAMO)

Condition-monitoring sensor technology and software systems can provide the information plant operators and regulators need to make reliability and risk-based decisions for plant maintenance and operations. However, a system representation (model or simulation) of the plant must be integrated with the sensor data and trending information to support the decision process. Ideally, maintenance is performed just before a failure occurs, and operations are carried out at or near the full capacity of systems and equipment. If this could be done safely (without excessive margin), then power generation would be most efficient. R&D could help establish how and to what extent advanced hardware, software, and systems modeling could incorporate CAMO into existing and new-design power plants. As conditions change within plant equipment and systems, maintenance schedules and operation could be modified and optimized.

2.) On-line Monitoring

Research should be conducted to support on-line monitoring, fault detection, situation assessment/diagnosis, and response planning through the use of advanced instrumentation and computer and computational technology. The challenge is to enable the systems to perform difficult cognitive tasks and be fully integrated into the operational environment. R&D is needed to replace some calibrations and to demonstrate higher reliability of the equipment by quicker diagnosis of failure or degradation beyond operability requirements.

3.) Virtual Reality for Maintenance Planning and Operations

Virtual reality is rapidly becoming an accepted design, operation, and maintenance tool in many industries. It provides a mechanism for creating a three-dimensional, virtual power plant that accurately represents plant systems, components, and operating conditions. In the case of non-routine and/or complicated procedures in normal operations and maintenance, a virtual test bed can help to develop the procedures, test them and train plant staff. The objective of the research would be to develop a virtual system that would represent the actual plant and/or component environment. In addition, techniques and technologies should be developed that allow staff to interact effectively with the virtual world, incorporating simulation of real-world feedback and consequences. (Please see more extensive write-up in the Simulation section.)

4.) Simulation for Maintenance Planning

Maintenance, certification, testing, and startup are significant cost drivers within the nuclear industry. Often the shutdown is extended due to interference between jobs, unexpected work, or misunderstanding between work groups. Simulation software should be developed that enables the user to schedule maintenance, train workers, examine the work to be performed at any given moment, adjust plans to avoid interference, and consider the impact of unexpected problems. The research issues include the development of methodologies and algorithms for maintenance planning, the development of complete, low-cost, three-dimensional models of plant components, and coupling these models to the design and operations models (see simulation section).

Benefits would include reduced downtime and reduced exposures to crews for tasks performed in hot or dirty environments.

5.) On-Line Robotic Maintenance

In many cases NPP maintenance must be performed off-line. The use of robotics may allow on-line maintenance of some systems, allowing shorter outage times and lower personnel exposures. Research is needed to identify systems, structures and components conducive to robotic maintenance, change NPP design to facilitate such maintenance (e.g. access and workspace), and develop robotic capabilities unique to nuclear servicing requirements.

6.) Self-Healing Systems

Moving past smart sensors and components, long-term research is needed to develop components and systems that have self-healing capabilities--i.e., they repair themselves. Today, work is being done on self-configuring computers that avoid damaged areas. In the future, the types of self-repairing systems should be expanded, for example, by creating novel materials that heal surface defects and avoid corrosion, or by devising automated annealing processes that achieve and maintain desired material properties guided by embedded sensors.

Modeling and Simulation

The design and operation of NPPs involves multiple interacting, dynamic, and time-dependent factors and phenomena. Current analysis and design codes were developed 10 to 30 years ago, when computers and computational algorithms were orders of magnitude less powerful than they are today and our understanding of nuclear plant phenomena was less mature. It is now possible to conceive of codes that incorporate realistic phenomenology, integrate all the relevant physics and engineering, couple between micro-scale and macro-scale processes, and/or that can simulate plant behavior in real time (or faster). In addition, modeling technology could be advanced to allow the use of the same model from birth of the plant concept, through design, construction, licensing, maintenance and operations, and to decommissioning. Virtual-reality simulations could become valuable tools for plant design, licensing, severe-accident analysis, operations, and maintenance. Several promising long-term research areas are suggested here.

1.) High Fidelity Phenomenological Simulation

Certain critical phenomena are important in determination of plant operating conditions, operational limits and facility and component life. This phenomenology is often represented in a simplified manner in analyses that are used in setting operational limits and lifetimes. In some cases, more accurate prediction of the physical phenomena may identify overly conservative limits to plant operation and lifetimes, suggesting the possibility of operating the plant more economically and for longer times, without sacrificing safety or reliability. Advances in physics models and computational capability are becoming available that permit a first-principles assessment of such phenomenology. The objective of this research would be to select specific phenomena, develop appropriate mathematical models and advanced computational techniques, verify and validate the capability to predict the phenomena, and make the developed computational tools broadly available.

2.) Multi-Physics Simulation

The operation of nuclear power plants involves multiple interacting phenomena, which are typically examined on an individual basis or coupled together in an approximate systems analysis framework that was state-of-the-art at the time of its development in the 1970's and 1980's. In some cases, a higher degree of modeling capability has developed for the individual phenomena, but the questions of interest are related to the interaction of these phenomena. The objective of this research would be to identify areas where coupled effects are critical and to develop mathematical and computational techniques for the integration of these high fidelity models to examine tightly coupled systems. Some promising areas include: fuel-failure models, severe-accident models, material-damage models (under much higher temperatures), thermal-fluid models in much different ranges of temperatures and for different fluids, and human-cognitive models. These programs are expected to take advantage of recent and ongoing advances in numerical algorithms, mathematical software and high performance computing technology.

3.) Large-Scale, High-Fidelity Integrated Systems Analysis

Under normal, off-normal and accident conditions, NPP performance involves a complex set of interacting systems, components and phenomenology. The computational infrastructure exists today to run higher fidelity models of important phenomena, examine complex interactions, and include greater fidelity in the representation of critical systems and components. Such a comprehensive and integrated plant representation could help to quantify the conservatism in operations and identify the potential for enhanced economics, while maintaining or improving safety and reliability. The objective of this research is the development of the next generation of systems analysis codes, which take advantage of developments in mathematical modeling, numerical algorithms and high performance, massively parallel computing. In addition to the development of accurate first-principles simulation models that may represent short- and long-term behavior of the entire NPP systems, effort should be made in the near term to develop integrated software that merges a number of existing systems codes in an efficient and consistent manner. One such example could be the consolidation of the RELAP-family of codes, for primary loop dynamics, with the CONTAIN-family codes for containment behavior. Another example would be the coupling of PRA simulations with thermal-fluid simulations to allow direct analysis of the effects of failure criteria and substantially aid reactor design. This research area should also address mathematical and computational issues associated with describing interacting phenomena with potentially large differences in time scales, the interpretation of large amounts of computed data, the role of scientific visualization technology and the verification and validation of the resulting models.

4.) Statistical Model for Component Reliability and Degradation Monitoring

One of the key incentives for implementing advanced I/C technology in future NPPs will be the ability to detect and identify degradations and incipient failures in plant components and systems. This ability will be of critical importance in prioritizing maintenance during the planned outages or for performing online repairs as needed. This will obviously help reduce the outage time and hence the operating cost, and would be of considerable benefit in risk-informed maintenance approaches, even for the current generation of NPPs. For this purpose, component reliability data, in proper statistical structure, could be used together with accurate simulation models to provide the component degradation monitoring capability.

5.) Combination of Simulation Models and I&C Algorithms

Implementation of advanced diagnostics and controls (D&C) software in future NPP control rooms and I&C applications will benefit significantly from the use of accurate simulation models. The *H-inf* control theory requires a simulation model as an integral part of the overall algorithm, although the control algorithm is structured to account for a certain degree of uncertainties or deviations from reference predictions. Statistical approaches for component degradation monitoring would also require plant simulation models. For these D&C purposes, the simulation models should be developed so that the full-blown first-principles capability of a high-fidelity NPP code may not be required. Instead, component-level simulation models of sufficient fidelity could be structured to yield efficient interfaces for various D&C applications. The interface between detailed nonlinear simulation models and D&C software should in general allow for dynamic structure as the system evolves in a particular event and different components of the plant begin to play more dominant roles in the system dynamics.

6.) Real-Time Simulation

Real-time simulation uses numerical models based on the fundamental physical principals of the process involved that run fast enough to permit real-time decision making. Currently, several simple real- time models link thermodynamic properties, equations of state, and the conservation equation of energy, mass, and momentum to develop an understanding of how global changes affect plant operation. This capability needs to be extended to include detailed models of fluid flow and heat transfer to provide accurate real-time simulations, achieving the detail available in computational fluid dynamics and finite element analysis of stress and heat transfer. These models will enable smart control systems, virtual power plants, operator informed decision making, and will enable coupling across a wide range of scales and systems.

The key research issue is the development of methodologies and algorithms to allow real-time analysis of system performance. Faster, bigger, less expensive computers will help enable the analysis but are not the solution for developing real-time simulation capability. The software must be able to couple various systems together, calculate only those regions and systems affected, and determine the accuracy of the calculation, plus provide the results to the operators in an instantly understandable way.

7.) Virtual Reality

Virtual reality describes a variety of experiences ranging from three-dimensional visualization to fully immersive and interactive synthetic environments. As used here, "virtual reality" is a three-dimensional, computer-generated environment that the user can move around in, view from many different perspectives, interact with, and modify. When coupled with an expert in the area of interest (e.g. a manufacturing engineer, an architect, or a medical doctor), virtual reality can catalyze breakthroughs in our knowledge and understanding.

Key aspects of the virtual experience include immersion and interactivity. Immersion refers to the degree to which the individual is fully encompassed within the virtual environment. Interactivity refers not only to the degree that the user can move around and change perspective, but also to the degree that the user can change and mold the environment. This capability to interact with the data holds significant potential. The user could physically alter a component in a virtual power plant and see the impact of this change on the system. For example:

- A design engineer could change the size of a pipe and see the impact on the flow in the system.
- The construction path for a plant could be completely laid out and explored by all the affected groups, reducing the construction time and interferences between component installation.
- The design of a heat exchanger could be examined by altering the geometry, thickness, or spacing of any or all of the components and would immediately see the changes in heat transfer and fluid flow on both sides of the heat exchanger.
- A trained operator could examine the fully three-dimensional flow pattern within the core noting any changes from the expected.

Virtual reality also provides a tool through which information can be examined and shared at a variety of levels. For example, an engineering team based in a number of geographical locations could interact directly with the virtual pilot plant at a number of locations simultaneously and to see the results immediately.

Research specific to nuclear power would include the development of virtual models of components, of real-time simulation capability for plant operation, and of the human-machine interface.

Human Factors and Human-Machine Interface

1.) Human-System Interface

The Human-System Interface (HSI) is composed of numerous resources including alarms, displays, procedures, support systems, and controls. These resources are integrated into workstations and control rooms (and other facilities, such as remote shutdown stations and technical support centers). In current control rooms, there is a limited range of devices used for HSIs. For example, plant information is largely displayed on strip charts, meters, gauges, simple digitized numeric displays, and simple computer graphics, such as, mimic displays. Computer technology offers great power to improve these interfaces. For example, plant parameters can be integrated in computer graphics forms, such as graphic displays based on the Rankine Cycle, intended to present information at a higher more usable level. Processing of lower-level information can be done by a computer not by the operator. Research is needed to define appropriate application of the technology and to develop guidance so the HSIs do not confuse operators and lead to increased error.

2.) Developing Fundamental Base of Knowledge on Human Factors

One roadblock to successful integration of personnel into advanced systems is our limited knowledge about the human processes involved in NPP monitoring and control. Such research will form a technical basis to greatly advance the design of control rooms and the interfaces used by personnel to perform their rolls. This research would build on and complement human-factors knowledge developed in other environments. Key examples of such research topics include:

- Understanding the relationship between automation and operator vigilance, confidence, and ability to assume control when automation malfunctions. This knowledge will contribute to the development of more "operator-friendly" automation and considerations of staffing reduction.
- Understanding of the cognitive process used by crew members to perform situation assessment, diagnosis, and plan responses. This will support the design of better displays, procedures, and operator support systems.
- Understanding how teams best function, communicate, and coordinate their activities. One of the significant effects of advanced technology is on crew interaction. This research will help to develop advanced control room with appropriate design for crew interaction, communication, and coordination.
- Understand how crews handle events that are unanticipated by designers, unplanned, and for which operators are not trained. Better understanding of how crews can handle such “beyond-design-basis accidents” can lead to improved procedures and HSIs, and reduce the risk associated with such complex events.
- Understanding how training will have to be changed to address the effects of advanced technology and the changing human role in new, more advanced plant designs. Also, research needs to address how advances in training can lead to more effective training for operations and maintenance crews.
- Understanding the relationship between technology and human error mechanism. This research will lead to advances in the design of error relevant systems (in *** error reduction, error detection, and error recovery).

V. Recommended Role for DOE

DOE’s role is to sponsor R&D with significant societal benefits that won’t happen without government involvement, due to risk, long-time horizon, or inadequate economic benefit for a commercial sponsor. A very important role is to fund the development of software, facilities, and knowledge that should be available to and shared freely by all interested parties, rather than held on a proprietary basis for the economic benefit of its developer/discoverer. DOE could use its available infrastructure and other venues for demonstration of initial R&D applications (for example, its nuclear and accelerator facilities and projects, nuclear material management and control systems, university research reactors, and international resources such as International Atomic Energy Agency (IAEA) material tracking, etc.). When DOE owns facilities for its own purposes, it should fund or co-sponsor any non-proprietary R&D using these facilities to research or test models, instrumentation, controls approaches, etc. of possible application to current and future generations of NPPs.

DOE should support the initial regulatory approval costs under certain circumstances (sensor performance in harsh nuclear environments/incremental improvements needed by nuclear only). NE should sponsor NP-related research as a component of any DOE-wide initiatives in advanced simulation (e.g. IT^2), and provide access to its computational facilities and code-development capabilities comparable to the access provided to other energy technologies. DOE should establish and maintain ties to other agencies with similar advanced I&C needs (e.g., DOT, FAA, NRC, NASA, DOD, DOC, standards organizations). DOE should facilitate and fund cooperative R&D, domestic and foreign involving NRC, nuclear industry and advanced technologist (industry, university, laboratories). DOE should sponsor human-factors R&D and studies on populations drawing from the entire NP industry, and to promote human resource development at the interface between I&C/simulation technology and NPPs.

Appendix H

Working Group Report on – Advanced Nuclear Fuels/Fuel Cycles

Nuclear Energy Research Advisory Committee

Subcommittee for Long Term Planning for Nuclear Energy Research

Summary Report
Advanced Nuclear Fuel/Fuel Cycle Working Group
December 8-10, 1999 Workshop

.

NERAC 2nd Strategic Planning Workshop, December, 1999

Advanced Nuclear Fuel Cycles Breakout Group Report

Introduction

The Advanced Nuclear Fuel Cycles Breakout Group (hereafter referred to as "the Group") discussed a wide range of fuels R&D needs associated with currently-installed commercial reactors ("generation 2" or "Gen 2"), the now available advanced light water reactors (Gen 3), some of which utilize Gen 2 fuel designs, and the reactors yet to be developed but anticipated to meet emerging power generation needs in the 21st century, and beyond (Gen 4). These issues and envisioned R&D activities were categorized into 6 research areas, which form the following 6 subsections of this report:

1. Higher-burnup Fuel for Gen-2 and Gen-3 Reactors
2. Gen 4 Fuels and Fuel Cycles
3. Fuel Operational Limit Phenomena
4. Th Fuel Cycle
5. Recycle/Reuse Technology
6. Enabling and Cross-Cutting Technologies

The issues and benefits that motivate the envisioned R&D in each of these areas were identified as were the challenges or barriers that would be addressed by R&D. Finally, specific research recommendations were developed for each identified research area, which included recommendations for subject matter as well as for approach. During the course of discussion, issues related to advanced nuclear fuel cycles and, more generally, nuclear energy R&D were discussed but determined to not be well classified within the six identified research areas. The essential substance of those discussions is reported in a separate subsection of this report, entitled Institutional Issues.

Higher-burnup Fuel

It was discussed that of the nation's 100-plus operating LWRs, as many as 90 would re-licensed for operation to about 2040. Therefore, improvements made to the current LWR fuel cycle in the next 10 to 20 years would have far-reaching impact. Group participants expressed that reactor-operating utilities are becoming increasingly interested in irradiating fuel beyond current burnup limits, which could have significant economic benefit. Therefore, higher-burnup fuel for current LWRs and potential advanced light water reactors is addressed specifically.

Drivers/Benefits:

> Economics. The ability to irradiate fuel to higher burnup will enable plants to operate with longer cycle lengths (assuming that typical outage activities can be accommodated accordingly) and with more efficient fuel utilization.

.

Proliferation Resistance. U.S. policy makers are increasingly interested in ensuring that nuclear fuel cycles are highly proliferation resistant. It is recognized that certain fresh- fuel compositions and longer in-reactor residence times (i.e., higher burnups) can each result in a spent fuel product that is unattractive for diversion to weapons.

Reliability. Operating costs are impacted by fuel failure rates; therefore, high reliability of fuel is important.

Safety. Although participants were careful to not imply that current reactor fuel designs are not safe, it was agreed that safety can be enhanced through improved fuel designs, which would facilitate licensing. It is noted that the NRC and EPRI are both engaged in a program to confirm the acceptability of the current peak rod burnup regulatory limit of 62 GWd/MTU, and possibly to provide a technical basis for increasing this limit.

Spent Fuel Disposal. Disposal of spent fuel from commercial reactors continues to be a concern to the public. It is agreed that higher-burnup fuels or fuel cycles could alleviate issues associated with spent fuel disposal by reducing the quantity of spent fuel to be disposed.

Spent Fuel Storage. Storage of spent fuel is a burden for operating utilities; therefore, reducing the amount of fuel to be stored prior to disposition would be beneficial.

Remove Incentive for Overseas Reprocessing. If new fuel designs offer improved economics and alleviate disposal issues, then incentives for reprocessing (i.e., separation of weapons-usable materials) can be reduced. This would further support U.S. non-proliferation policy.

Fuel Management Flexibility. Operational flexibility, including power upgrades, will likely be a key aspect of improving the economics of operating LWRs and advanced LWRs.

Challenges/Barriers:

Utility/industry. Acceptance of new fuel design that differ substantially from current designs will require in-pile verification of performance.

Regulatory. Implementation of significant changes to fuel design by licensees will require approval by the U.S. NRC, which requires that quality-assured analytic and experimental justification be provided. In addition, there are two generic limits, applicable to all vendors designs, which must be addressed: the 5% limit on U235 enrichment, and the 62 GWd/MTU on peak rod burnup.

Materials Performance Limitations. Fuel lifetime is currently limited by the degradation of cladding materials with increased exposure to reactor core environments. Advances with core and cladding materials will be required to realize higher-burnup potential.

.

Insufficient Data. Currently, performance data at burnup values above 70 GWD/MTU (PWR basis) for existing fuel designs is limited. Development of higher-burnup fuel designs will require an understanding of the limitations of existing designs.

Lack of Irradiation Facilities. Development of new fuel designs will require irradiation of test fuel to burnup values above those currently being achieved. Such extended irradiation can be demonstrated in lead test assemblies operated in commercial reactors; however, if new fuel designs differ substantially from current designs, then government-owned test reactors are better suited to irradiate such fuel and assess fuel failure limits and post failure performance.

Enrichment Limitations (criticality and infrastructure limitations). The lack of criticality safety benchmark data for uranium enrichments greater than 5% U-235 (and less than 20%) makes difficult the licensing of commercial fuel facilities (throughout the fuel cycle chain) for higher enrichments. Also, the equipment in many facilities may not be capable of safely processing higher-enrichment uranium without modification.

Accommodation of Industrial Proprietary Interests. Although commercial proprietary interests can be accommodated in government-funded R&D programs, such accommodation must be considered from the outset of the program.

Implications for Handling, Storage, and Disposal of Spent Fuel. Fuel irradiated to higher burnup will have more fission products and minor actinides than current spent fuels (and, therefore, a higher decay heat loads and higher source term). Existing methods and licenses for managing spent fuel will need re-evaluation for higher-burnup fuel.

Predictive and Safety Analysis Capabilities. The techniques used currently for predicition of core behavior and for safety analysis will need to be evaluated for addressing use of higher-burnup fuel designs, and modified as appropriate.

Specific Research Recommendations

The Group proposes that NERAC recommend a joint government-industry program, similar in nature to the High Burnup Fuel Program of the 1980s. Such a program should include the following elements:

- The objective should be development of robust fuel designs capable of up to 100 GWD/MTU (batch average).

- The program should include hot cell examination of current fuel designs to enable an understanding of life-limiting phenomena, and to provide a foundation for increasing the burnup capability of existing designs.

- The program should include in-core performance assessment so that operating characteristics of higher-burnup fuel can be identified.

.

- The program should include provision for obtaining criticality safety data for benchmarking of codes and methods to address enrichments above 5% and development of the regulatory infrastructure to support licensing of fuel at the increased enrichment.

- International participation should be sought, because the expected costs of a program would be sufficiently high that non-U.S. contributors (which would benefit from the results of the program) will be needed to share costs.

- International and university participation are desired to ensure that all potential innovations are considered for applicability and to aid in the development of new professionals through the universities.

- The program will require development of advanced fuel, cladding, and control materials if higher-burnup capability is to be attained.

- The program should build off of Advanced Materials and Fuels Technology program.
- The program should be complementary to the EPRI-NRC Robust Fuels Program.
- The Program can be considered a transition to more advanced Gen-4 concepts.

Gen-4 Fuels and Fuel Cycles

The Group agreed that the U.S. should embark upon a R&D program to develop a generation of reactors to be implemented in the next century. The Group further accepted the concept of a generation-4 (Gen-4) reactor concept as described by DOE-NE director, Bill Magwood, in several speeches and presentations. Because the general scope of R&D to address future reactor designs was being addressed by another breakout group, the Group pointedly considered only fuels and fuel cycles that might be used for such reactor designs. The discussion was intended to address fuel issues that would apply generally to any such reactor program, although it is acknowledged that issues associated with more exotic fuel concepts (e.g., liquid fuels) were not fully considered.

Drivers/Benefits:

Requirement for Anticipated Reactor Development. Regardless of the reactor technology (or technologies) to be pursued in any future reactor development program in the U.S., fuel and fuel cycle technology development will be a major component - both in the selection of the concept, and in its development.

Operational Safety (deployment considerations). It is believed that operational safety for the envisioned deployment of the reactor system(s) can be enhanced by development of a new fuel form and fuel cycle.

Enhanced Proliferation Resistance. Fuel technology will be a key component of a reactor system designed for enhanced proliferation resistance.

.

Enhanced Resource Utilization. Fuel cycles developed for use with new reactor technologies are expected to allow more efficient utilization of fuel resources, through characteristics such as high-burnup capability, higher conversion ratio, etc.

High Reliability and Robustness. Simple and inexpensive operation of any new reactor designs will require low fuel failure rates (particularly for long lifetime, modular cores where fuel reconstitution and repair during an outage is not an option) and, perhaps, the ability to operate in a load-following mode.

Waste Minimization. Objectives for development of any new fuel cycle should include the minimization of waste.

Remove Incentive for New Fuel Handling Infrastructure at Deployment Sites. Depending on the reactor technology to be considered, a new design might obviate the need for fuel handling facilities at or near the reactor site. If such a system were deployed in a developing country, for example, then proliferation resistance is aided if that nation is not compelled to construct facilities to handle or process spent fuel.

<u>Challenges/Barriers</u>:

Materials Performance Limitations. Advances with core and cladding materials will be required if new reactor designs will utilize corrosive coolants (e.g., lead or lead-bismuth) or higher temperatures.

Gaining Access to Defense-Related Data and Performance Modeling. Participants in the group suggested that fuel development performed previously in the defense programs areas might be relevant to R&D for new reactor fuel systems. Gaining access to such information will be governed by National Security considerations, including energy security.

Lack of Appropriate Test Facilities. Development of fuel for new reactor concepts will require irradiation testing under prototypic conditions. For some systems now being proposed (e.g., lead-bismuth-cooled or gas-cooled reactors) prototypic test facilities do not exist in the U.S.

Integration to Emerging Reactor Development Program. Because development of new fuel cycles and new fuel forms consists of long lead-time activities, it is anticipated that some fuel development work would proceed in parallel with development of reactor concepts. It will be important that the fuel cycle development program is integrated with the reactor development program as it evolves.

Predictive and Safety Analysis Capabilities. New reactor and fuel concepts will require development of new models and analytical capabilities. The lack of such models (or the information with which to develop such models) will limit the extent of concept evaluation that can be performed using simulation tools.

.

Enrichment Limitations (criticality and infrastructure limitations). The lack of criticality safety benchmark data for uranium enrichments greater than 5% U-235 (and less than 20%) makes difficult the licensing of commercial fuel facilities (throughout the fuel cycle chain) for higher enrichments. Also, the equipment in many facilities may not be capable of safely processing higher-enrichment uranium without modification. If higher-enrichment uranium is to be used for Gen-4 systems, then this issue must be addressed, as is the case for higher-burnup fuels for current reactors.

Question of Industrial Supply of Selected Materials. Innovative reactor designs may employ corrosive coolants or high coolant temperatures, requiring utilization of core and cladding materials not normally available commercially. Industrial supplies of such materials would need to be considered when planning R&D programs.

Specific Research Recommendations

The Group proposes that NERAC recommend research programs that consider the following:

- long-life cores (e.g., no refueling for 10+ years or cores that are designed for the duration of the plant life; Gen 2 and en 3 cores are addressed under Higher-burnup Fuel)
- robustness
- passive fuel and core response (i.e., benign consequences of fuel failure or benign fuel response to off-normal events)
- high-temperature fuel and materials performance
- incorporation of advanced information technology and "smart" technology into fuel management and fuel cycle concepts
- fuel-cycle front-end technologies (the front end of the fuel cycle was not addressed specifically in the proceedings; however, it was recognized that advances in technologies used to prepare fuel feed materials may well have beneficial impact on economics or waste management.)

Fuel Operational Limit Phenomena

Some Group participants advised that some operational limits placed on current plants are attributable to uncertainties in safety analyses. A particular example of this is the limits on channel power of PWRs imposed due to uncertainties in thermal hydraulic phenomena. Therefore, the Group proposes R&D to achieve better understanding of nuclear materials and fuel thermal and hydraulic phenomena that impact fuel operating limits and margins in Gen-2 and Gen-3 reactor systems.

Drivers/Benefits:

Improved Economics from Operational Flexibility. If limits can be made less restrictive, then plant operators can better optimize core loadings, thereby allowing better fuel utilization, and seek power upgrades.

Reduction of Waste Associated with Fuel Usage. Better fuel utilization means fewer fuel assemblies used, which also means less fuel handling-associated waste.

Better-Defined Safety Margins. Reducing uncertainty in safety-related calculations will enable operators and regulators to know more precisely the safety margin for a given set of conditions.

Development of Better Analytical Tools. The key to reducing calculational uncertainties is incorporation of better models and better analytical tools - those models and tools would be available for other analytical needs.

International Interest in Topic. The international interest in an effort to address this concern provides an excellent opportunity for the U.S. DOE to collaborate with other nations.

Challenges/Barriers:

NRC Acceptance Uncertain. Clearly, any new approach to calculating safety margins would be successful only if the U.S. NRC accepts the new methods, which is currently uncertain. Therefore, some indication (and perhaps guidance) should be sought from the U.S. NRC.

Utilization Limited to Specific Applications. Although the models and techniques to be used to address these issues have broader applicability to LWRs, the applications are limited.

Complexity of Models Required. Modeling complex thermalhydraulic phenomena is not simple. Therefore, this will be a technically challenging problem.

Specific Research Recommendations

The Group proposes that NERAC recommend research programs that includes:

- thermal-hydraulics, materials, and nuclear phenomena (including post-failure phenomena) experimentation to benchmark existing models and to support the development of new models
- development of improved computational models

Th Fuel Cycle

The Group consensus was that the potential of Th fuel cycles should be re-considered. Some participants cited experience or research results that indicate that Th fuels may be attractive for intermediate-term and long-term application.

Drivers/Benefits:

Th/U-233 Fuel Cycle is Only Alternative to U/Pu. The U/Pu fuel cycle has been studied and developed extensively over the last several decades. However, the Th/U-233 fuel cycle has not been considered in similar detail, and it is the only long-term alternative to a U/Pu fuel cycle.

.

Non-Proliferation. The radiation levels and chemistry associated with Th fuel cycles may effectively render Th-based fuel systems unattractive for diversion into weapons uses.

Potential Economic Benefit through Long-Term Conversion and Simplified Reactivity Management. The enhanced conversion that appears possible with Th-based fuels in thermal reactors may lead to extended burnup fuel designs. Simpler reactivity management schemes through a cycle would also be possible.

Chemical Stability of Form for Direct Disposal. The relative stability of ThO_2 (compared to that of UO_2) indicates that ThO_2 may be more durable in a repository.

Chemical Stability of Form for Operational and Safety Considerations. . The relative stability of ThO_2 (compared to that of UO_2) indicates that ThO_2 may be less reactive with reactor coolant (for example, during a failed-fuel event).

Resource Availability and Utilization. The reserves of Th are larger than reserves of uranium, indicating that Th can provide a long-term energy source.

Best (only) Alternative for Enhanced Conversion in LWRs (exclusive of recycle). A Th fuel cycle is the best identifiable alternative for incorporating enhanced conversion into LWR fuel cycles without fuel recycle.

Potentially Better Fuel Form for Gen-4. The attractive attributes of proposed Th fuel forms might be applicable to Gen-4 concepts as well as Gen-2 and Gen-3 reactors.

Effective for Enhanced Pu Consumption. Th-based fuels that incorporate separated Pu (or weapons Pu) would provide a means to reduce separated Pu inventories using the current base of reactors.

Challenges/Barriers:

Radiation Fields of Th-Based Fuels Impact Handling Requirements. The daughters and activation products of Th isotopes have significantly strong radiation fields, which may preclude fuel fabrication by conventional schemes.

Fabrication Difficulties. Fabrication of Th-based fuels may be more difficult than U-based fuels, and there is little experience with Th-based fuels.

Purity of Available Feed Materials. Because there is not currently a nuclear-related market for Th fuels, it is not clear that Th materials of the required purities will be available.

Less Operational Experience with Th Fuel Cycle.

No Infrastructure to Support Near-Term Implementation.

.

No Clear Incentive for Conversion of Current Reactors to Th-Based Fuel Cycle. Although implementation of a Th-based fuel cycle might meet U.S. non-proliferation objectives, it is not clear that a sufficient economic incentive exists to entice current reactor operators to seek licenses for Th-based fuels.

Lack of Fundamental Data. There is little known data for Th fuels and for the physics of Th reactor cores. Improving that database would require significant experimental resources.

Specific Research Recommendations

The Group proposes that NERAC recommend an R&D program to investigate and develop Th fuel cycle technology. However, the program should address a fuel cycle to be used in a Gen-4 reactor system rather than current reactor systems; this suggestion is made because the Group consensus was that a radical change to the current fuel cycle in LWRs in the U.S. is not likely. The R&D program should include the following elements:

- determination of proliferation resistance strategy to set requirements
- measurement of nuclear data
- assessment of irradiation performance of fuel designs
- development of fuel fabrication processes
- fuel materials property characterization
- assessment of core performance and safety

Recycle/Reuse Technology (incl. Non-power uses)

- Non-aqueous Recycle (pyro, AIROX-like)

The Group proposes that technology R&D on recycle and re-use technology be resumed to offer options to future decision makers and to enable the U.S. to credibly influence how other nations might implement nuclear technology. Such technology will have potential to improve the economics, the resource utilization, and the proliferation resistance of the existing once through cycle. The specific technologies that should be considered are non-aqueous technologies such as pyroprocessing and other "dry recycle" technologies (i.e., similar to AIROX or DUPIC). Non-power uses of recycle options should be considered, and might include separation of key fission product isotopes for medical or industrial use.

Drivers/Benefits:

Improve Utilization of Fuel Resources. Any decision to implement recycle technology will necessarily be driven by economic considerations and a desire to improve utilization of resources.

Non-Proliferation Through Intrinsic Barriers. A key motivation for the U.S. to engage in recycle technology development might be the desire to offer to other nations alternatives to technologies that are not as proliferation resistant as the U.S. would prefer. Development of technologies that incorporate instrinsic barriers to proliferation or diversion may be possible.

.

Utilization of a "Waste", Possibly for Non-Power Uses (i.e., supply of certain isotopes). Development of recycle technologies, or product-extraction technologies, will open the option of beneficial use of fission by-products.

Waste Management Improvements. Development of recycle technologies will increase the options available for waste management, perhaps reducing the quantity of waste to be disposed of and improving the economic viability of preferable nuclear energy technologies.

Opportunities for International Collaboration and Influence. Development and use of new recycle technologies, will enhance opportunity for international collaboration. Such collaboration enables the U.S. to influence development and selection of technologies for recycle overseas and to maintain technical understanding of technologies being developed in other nations.

Challenges/Barriers:

Clarification of Acceptability within National Non-Proliferation Policy. Successful initiation and implementation of a program to develop proliferation-resistant recycle technologies will clearly require clarification of the implications of U.S. non-proliferation policy.

U.S. Lags Behind Other Nations in Technology and Philosophy of Approach. The U.S. has not made important contributions to the international dialogue on acceptable recycle technologies for several years, and the U.S. has not been forced to consider the economic and waste management issues associated with recycle. Therefore, the U.S. may not be regarded as a serious contributor in this area until a substantial international collaboration is established.

Difficulty of Meeting Fuel Quality Requirements with Remote Processing and Fabrication Operations. There will be technical challenges to the preparation of acceptable-quality fuel from recycled materials.

Economics of Recycle and Re- Fabrication Techniques. Any new recycle technology developed in the U.S. must have the potential to reduce the overall fuel cycle costs for U.S. utilities, including the total cost of both the front end and the back end, including ultimate disposal.

Difficulty in Obtaining Irradiation Qualification Data in NRC-Regulated Facilities. Qualification of recycled fuel for use in existing reactors will require lead assembly irradiations in a licensed reactor.

Waste Management. New recycle technologies may produce new waste streams which must be considered in both the environmental and economic evaluation of the technologies benefits.

.

Specific Research Recommendations

The Group proposes that NERAC recommend an R&D program to develop non-aqueous recycle technologies. The program should include the following elements:

- identification of preferred alternatives for development
- development of waste management technologies
- development of fuel processing and fabrication technologies
- assessment of recycled fuel performance
- development of separation techniques for desired isotopes as by-products
- international collaboration
- incorporation of advanced information technology and "smart technology" into fuel cycle and monitoring concepts

Enabling and Cross-CuttingTechnologies

The Group recognized that some research activities that may be proposed will benefit more than a single-mission program. Because most envisioned R&D programs are expected to be focused toward meeting relatively narrow program objectives, the R&D that often leads to technology advances that benefits many programs, but is sufficiently high-risk to be unattractive to a single-purpose program, may not have advocacy. Although the Group did not reach consensus as to the specific elements of such R&D, it is proposed that R&D be supported to make advances in the general technology area of the fuel cycle.

Drivers/Benefits:

Provision of Fundamental Data or Technology to Support Innovations in Initiative Areas. For example, the R&D envisioned might help researchers better understand fundamental corrosion processes in reactor core environments, which will then enable the development of corrosion-resistant cladding alloys.

Conduct of R&D That Can Lead to Advances and Innovations. R&D conducted outside the immediate needs of a schedule-driven program can often lead to advances that can subsequently be incorporated into a program. For example, the R&D envisioned might develop concepts for innovative cladding materials applicable to many fuel concepts under consideration

Means of Incorporating Universities. An R&D program of the type envisioned provides an excellent means of incorporating university research into relevant topics, without requiring that university personnel be part of a schedule-driven, focused program - conditions that might stifle creativity that can come from university R&D and inhibit the training of graduate students.

Effective Mechanism for International Collaboration. Although nations may not agree on a particular approach to reactor or fuel cycle technology, collaboration on a technology R&D program of the type envisioned can enable common ground for collaboration. Such R&D

.

can also be conducted outside the realm of special technologies that nations may wish to keep proprietary.

Challenges/Barriers:

Available Facilities. Facilities for irradiation and post-irradiation examination of fuels and materials, particularly fast-spectrum facilities, are not conveniently available. Other facilities that are available are prohibitively expensive for smaller R&D efforts.

Instrumentation and Diagnostics. Development of new fuels and materials may require instruments and diagnostics that are yet to be developed.

Scaling and Experimental Techniques. Extrapolation of bench-scale R&D results to larger reactor systems will be a challenge, particularly if smaller and intermediate-size irradiation facilities are not available at reasonable cost.

Specific Research Recommendations

The Group proposes that NERAC recommend an Enabling and Cross-Cutting Technology R&D program for nuclear fuel cycle technology. Some suggested topics of research for this program include the following (although availability of resources would likely limit the scope of the program):

- research to understand fuel and materials degradation and failure mechanisms
- investigation of radiation-induced phenomena in fuels and materials
- research for enhanced understanding of physical phenomena and related modeling
- investigation of low-consequence failure phenomena (i.e., research into how fuel designs can be changed to make fuel response intrinsically benign after cladding breach.)
- research for in-reactor performance enhancement
- research to assess repository performance of disposed fuel and methods for enhancing repository performance
- research into advanced fuel fabrication techniques
- development of advanced absorber/control materials and techniques
- acquisition of additional nuclear data

Prioritization

The Group made only two comments regarding prioritization:

- Higher-burnup Fuels and Gen-4 Fuels and Fuel Cycles should be of highest and similar priority.
- Fuel Operational Limit Phenomena has prospect for near-term impact.

.

Institutional Issues

In the course of discussion, several issues were raised that were applicable to many of the research topics being considered by the Group, or that were applicable to many aspects of technology being addressed in the Workshop. These are listed here, with some explanation.

Note: the Group did no+t specifically address fuel enrichment technology R&D, other than to propose it as a component of Gen-4-related research. The group notes that fuel enrichment costs are an important part of the cost of the uranium fuel cycle and might be considered further in another effort. Also, enrichment of desired isotopes in other core components may be beneficial if enrichment costs can be reduced.

User facilities should be made available to smaller R&D programs, which will enable a better incorporation of experimental research into R&D programs. The Group noted a disturbing trend away from experimentally-based R&D, toward more computer-oriented R&D, due to the difficulty in obtaining funding for experimental programs. In addition, irradiation facilities and post-irradiation examination capability are not readily available to researchers in universities or in institutions other than national laboratories.

The Group recommends that Information Technology and supercomputing capabilities be implemented in all R&D areas. Focused application and development of advanced computing techniques for modeling and simulation to resolve issues should be incorporated where appropriate. Furthermore, the Group believes that Incorporate Information Technology and “smart” sensors should be incorporated into fuel cycle and management concepts where appropriate - such incorporation will improve the transparency of fuel cycles (improving proliferation resistance) and will likely enable more efficient operation.

Better technology transfer across DOE organizations is needed. DOE, in defense and navy programs, has developed various technologies that may significantly improve commercial fuel economics, burnup, and safety. This information should be made available to the industry. The taxpayers paid for it. With the end of the cold war, this type of information can now be released.

Education, Infrastructure, and New Technology Application: the Group, in general, believed that a new vision and focus for future R&D is needed to attract the next generation of researchers. The Group also advocates incorporating student research into Laboratory and industry R&D programs as a means of providing interesting experiences for these students.

Waste fee considerations and implications for fuel cycle decisions should be considered. For example, does the current scheme of levying high-level waste fees on a per-MW-hr basis influence our R&D priorities and commercial fuel cycle decisions in a way that is counter to U.S. national interests?

A new paradigm for international partnership on fuel and fuel cycle development should be sought. This paradigm should include efforts to stay abreast of developments in foreign research initiatives.

.

Participants

NERAC Strategic Planning Workshop

December, 1999

Advanced Nuclear Fuel Cycles Breakout Group

Name	Organization	E-Mail Address
Marvin Fertel (Chair)	NEI	msf@nei.org
Paul Turinsky	NCSU	turinsky@eos.ncsu.edu
Tom Isaacs	LLNL	isaacs2@llnl.gov
Tom Sanders	SNL	tlsande@sandia.gov
Tom Coleman	FCF	thomas_a_coleman@framatech.com
Tom Rodack	ABB	tom.rodack@us.abb.com
Al Solomon	Purdue	solomon@ecn.purdue.edu
Allen Croff	ORNL	agc@ornl.gov
Norton Haberman	DOE-NE	norton.haberman@hq.doe.gov
Phil MacDonald	INEEL	pem@inel.gov
David Diamond	BNL	diamond@bnl.gov
John Sackett	ANL	john.sackett@anl.gov
Alan Waltar	Texas A&M	waltar@trinity.tamu.edu
Herbert Feinroth	Gamma Engineering	feinroth@bellatlantic.net
Charles Forsberg	ORNL	cwf@ornl.gov
Mujid Kazimi	MIT	kazimi@mit.edu
Vic Reis	SAIC	reisv@saic.com
Doug Crawford	ANL	douglas.crawford@anl.gov