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

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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:

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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

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[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

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[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

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[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.

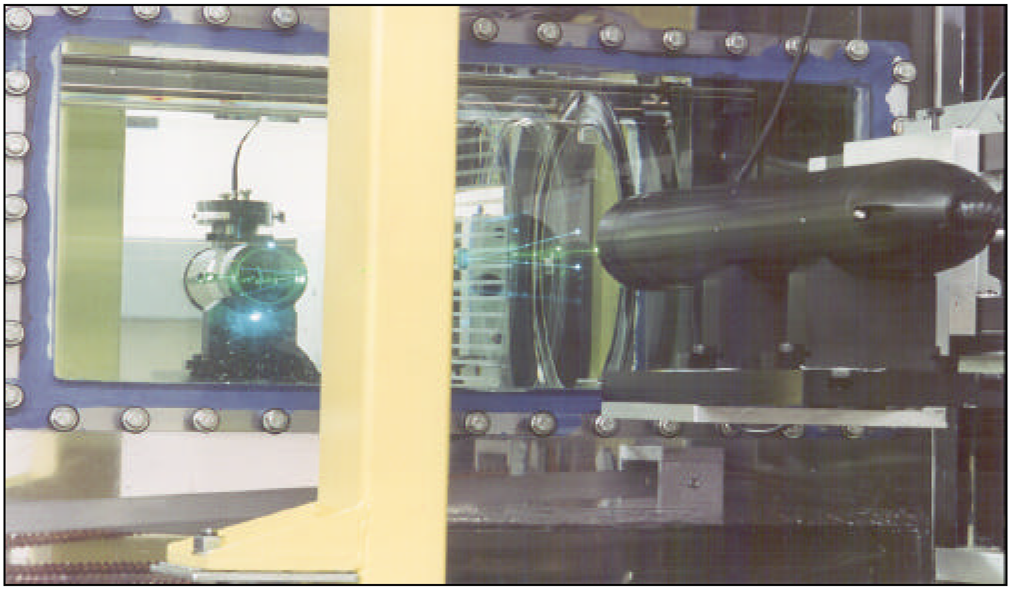

Figure 1. Laser doppler velocimetry apparatus used at Idaho National Engineering and Environmental Laboratory to study thermal fluid physics of high temperature flows in advanced reactors systems under an ongoing NERI Project.

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

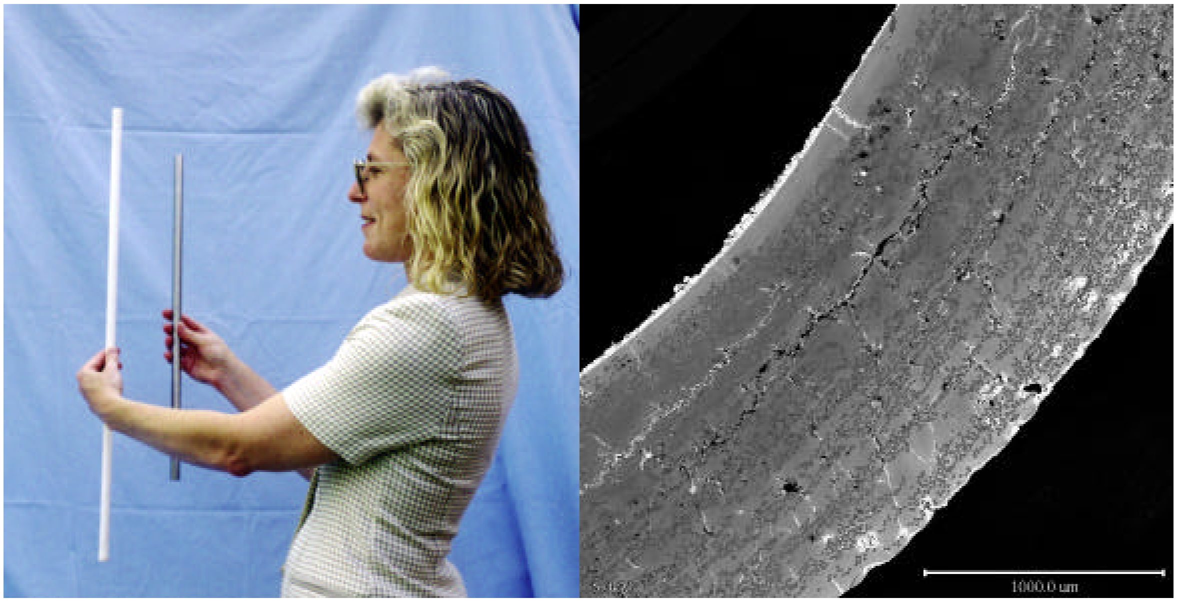

Figure 2. A new ceramic composite clad material is being evaluated by Gamma Engineering for potential nuclear applications under DOE's NERI Program. Left - NERI Project Manager Bonnie Packer holds a new ceramic tube and a traditional zircaloy clad tube used in commercial LWRs. Right – Microscopic cross-section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

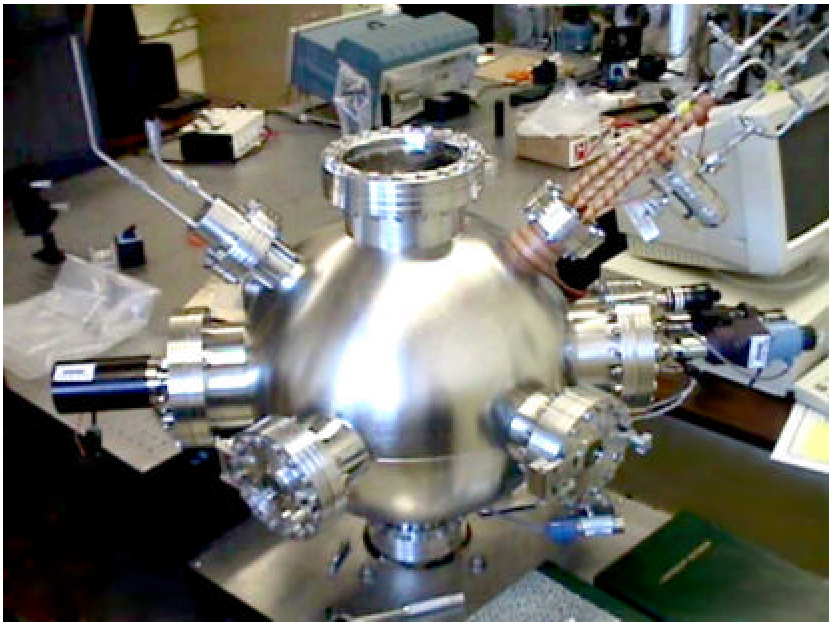

Figure 3. Laser Ablation Deposition Apparatus used at the University of Florida for ceramic corrosion protection systems for zircaloy cladding experiments under a NERI grant.

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.

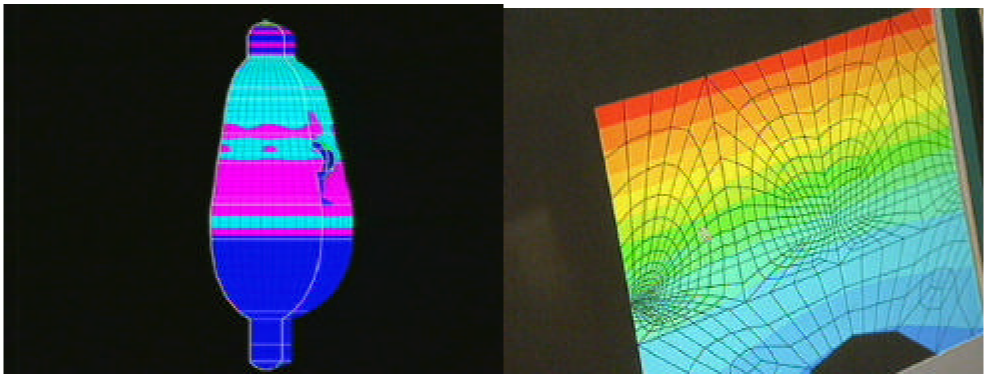

Figure 4. Computational modeling techniques for structural stress analysis are demonstrated at Sandia National Laboratories.

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.

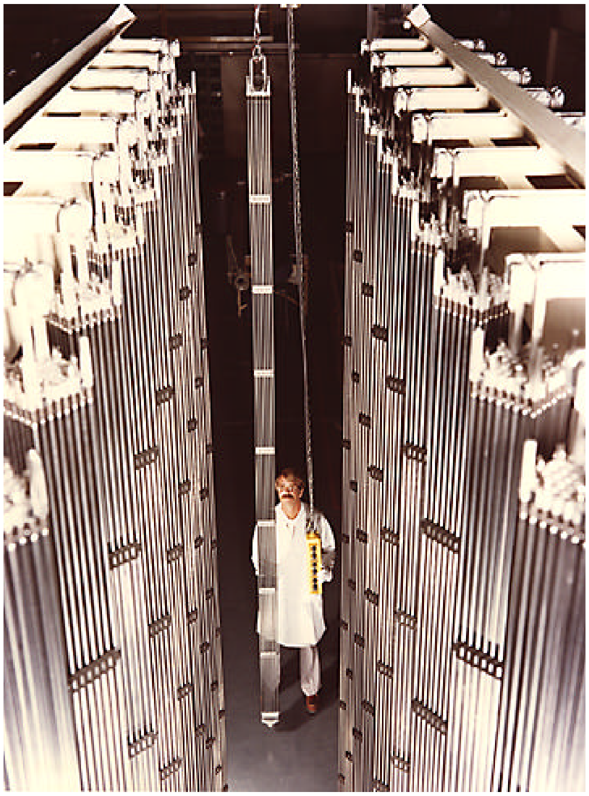

Figure 5. Typical pressurized water reactor fresh fuel assemblies

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.

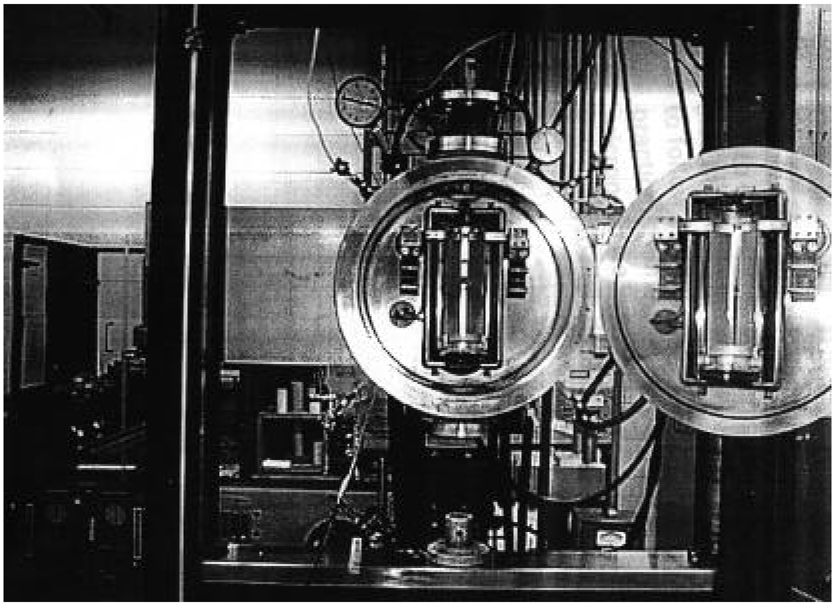

Figure 6. Purdue University sintering furnace; used for demonstrating advanced fuel fabrication techniques

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.

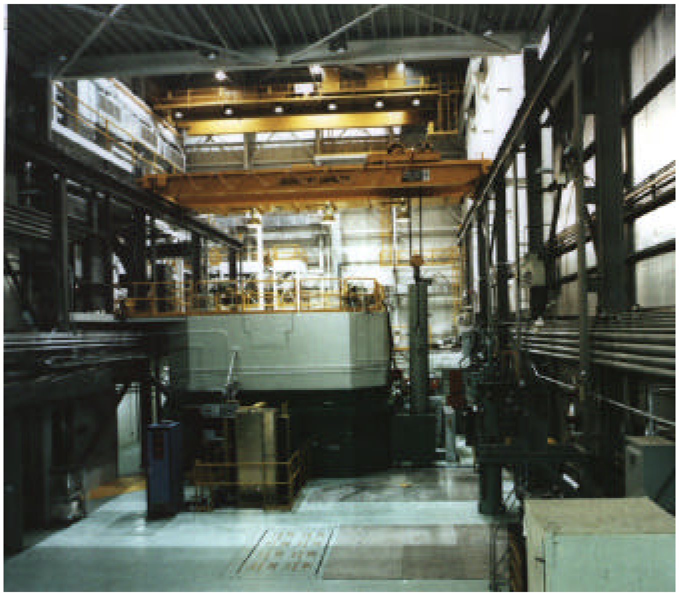

Figure 7. Transient Reactor Test Facility (TREAT) at Argonne National Laboratory (West)

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.

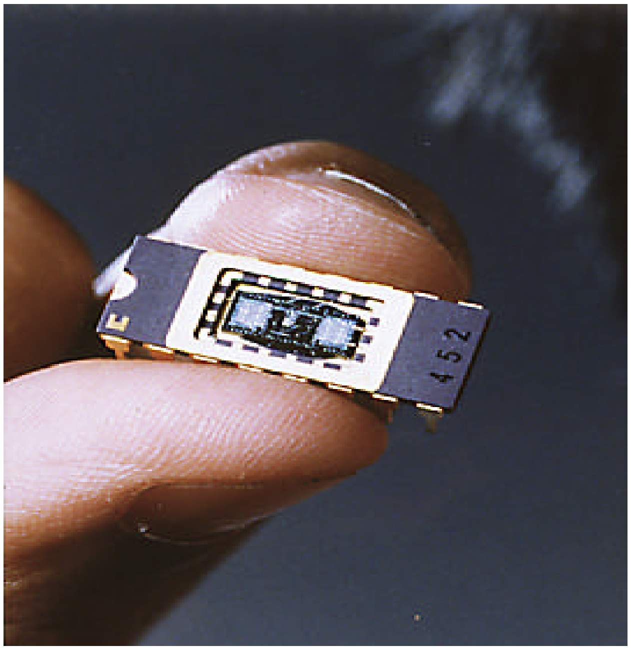

Figure 8. A researcher inspects a computer chip used in advanced control system circuits

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.

<u>Modeling, Simulation, and High Performance Computing</u>

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.

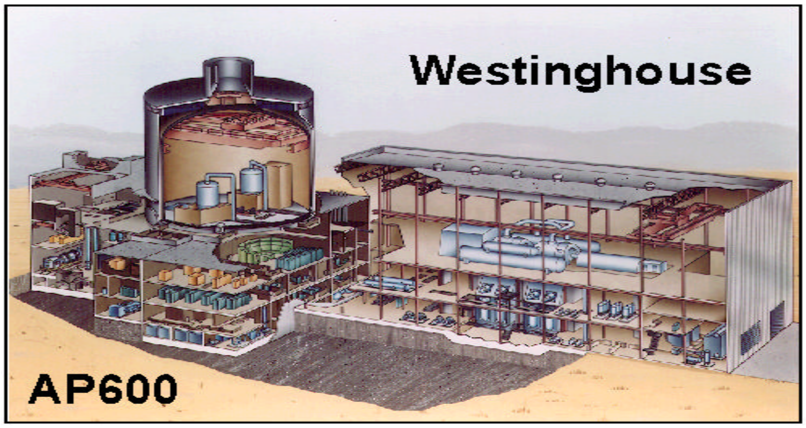

Figure 10. Westinghouse AP600 advanced light water reactor design (Generation III)

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.

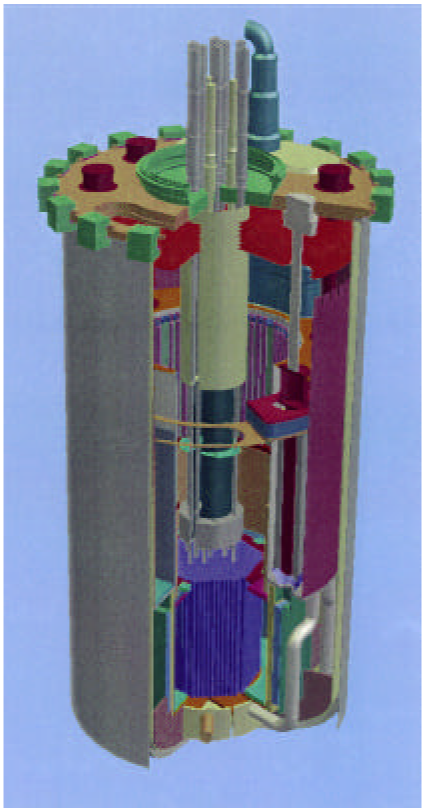

Figure 11. Concept drawing of General Electric's Super Prism advanced liquid metal reactor design

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).

<u>Efficiency/Output ($/KW or KWh)</u>

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).

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[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.

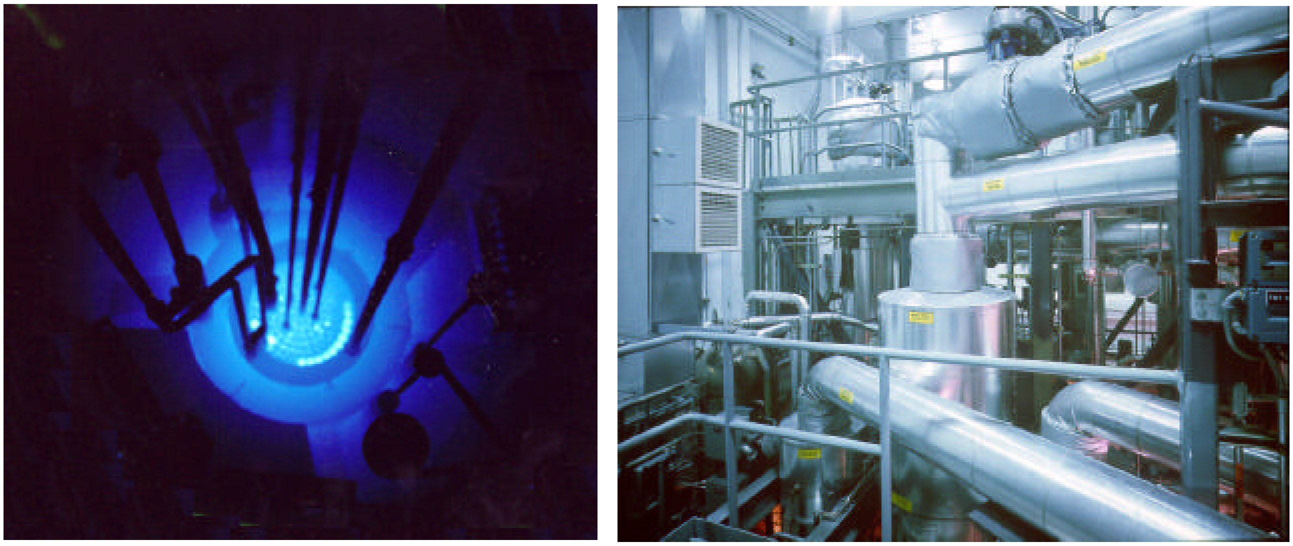

Figure 13. Some universities maintain nuclear engineering research facilities. Shown are the TRIGA research reactor and the APEX scaled ALWR test facility at Oregon State University.

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.

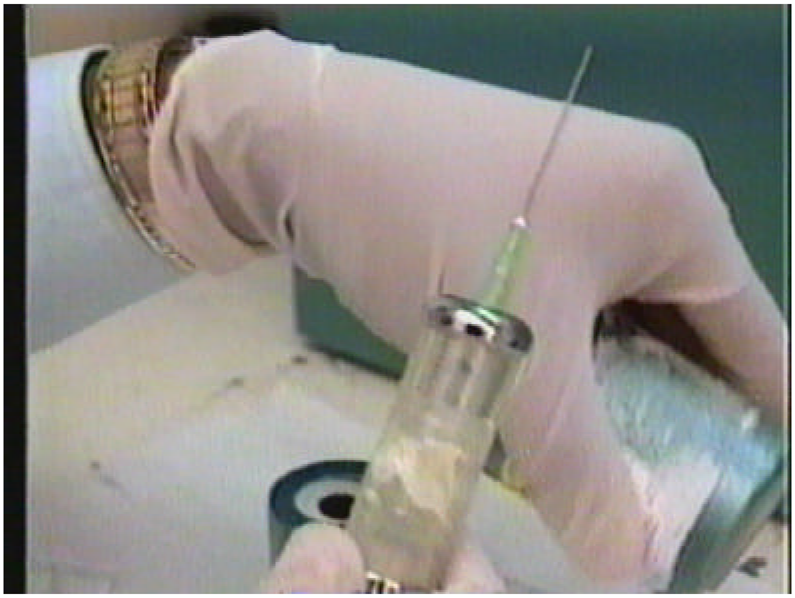

Figure 14. Injecting medical isotope tracers for diagnostic screening

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.

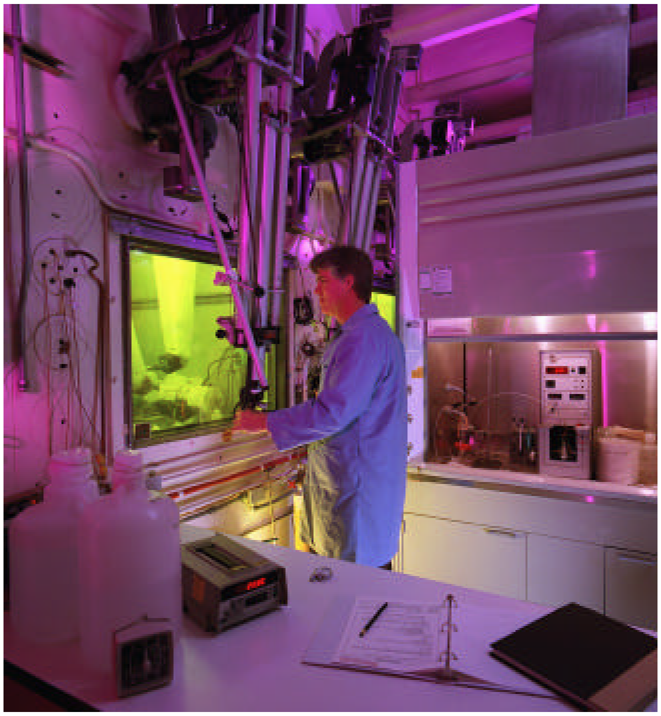

Figure 15. Handling radioisotopes in hot cell at Pacific Northwest National Laboratory's Radiochemical Processing Lab

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.

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[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.

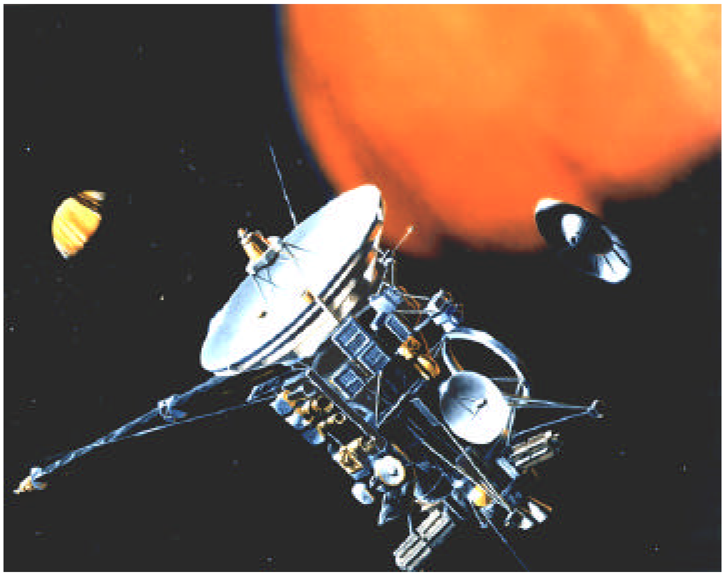

Figure 17. Artist's concept of Cassini spacecraft, launched in 1997 on a mission to explore Saturn. Cassini uses several Pu-238 radioisotope thermoelectric generators and heat sources.

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.