Nuclear Energy Research Advisory Committee

(NERAC)

Subcommittee on

Long-Term Planning for Nuclear Energy Research

Long-Term Nuclear Technology Research and Development Plan

SUMMARY

June 2000

SUMMARY

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

Introduction

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

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

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

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

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

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

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

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

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

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

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

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

Goals

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

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

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

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

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

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

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

Major policy issues which arise in this plan:

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

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

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

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

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

Programs covered in the report

Basic Research

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

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

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

Nuclear Power

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

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

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

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

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

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

Advanced Fuel Cycles

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

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

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

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

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

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

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

Reactor Technology and Economics

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

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

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

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

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

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

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

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

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

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

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

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

Isotopes and Radiation Sources

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

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

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

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

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

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

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

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

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

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

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

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

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

The following strategies are recommended to support isotope research:

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

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

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

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

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

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

Space Power Systems

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

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

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

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

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

Education and Training

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

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

NERI and NEPO

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

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

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

Other Key DOE Nuclear Energy Missions

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

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

Some of the associated issues require policy decisions:

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

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

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

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

International

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

Funding

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Total

In developing this plan, several fundamental assumptions were made:

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

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

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

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

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

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

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

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

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