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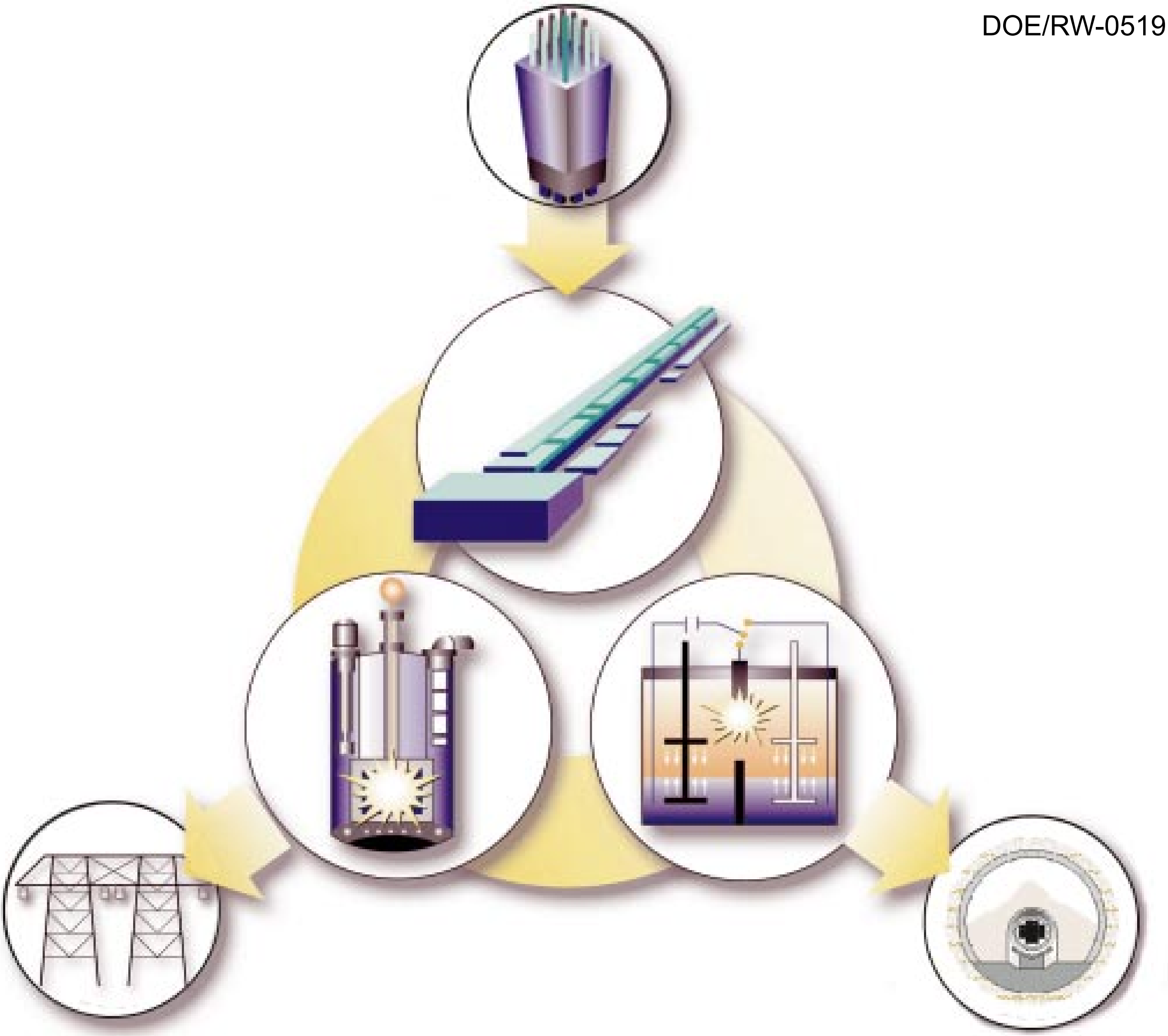

A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology

A Report to Congress

October 1999

DOE/RW-0519

A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology

A Report to Congress

October 1999

Department of Energy
Washington, DC 20585

November 1, 1999

Transmittal letter to the attached distribution

Dear Recipient:

The Conference Report accompanying the Fiscal Year 1999 Energy and Water Development Appropriation Act directed the Department, through the Office of Civilian Radioactive Waste Management, to conduct a study of accelerator transmutation of waste (ATW). In response to the Congressional direction, I am enclosing a copy of the report entitled: "A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology - A Report to Congress."

The report addresses the potential application of ATW to civilian spent nuclear fuel and responds to the specific issues raised in the Conference Report. The report includes status reports on international ATW technology programs, includes recommendations on the remaining critical technology, and identifies a science-based research program to address the formidable technical issues cited in the report.

The Administration makes no recommendation with regard to the panel's proposed research program. Should there be a national policy decision to pursue this technology, the expert group has identified a science-based research program to address the technical issues cited in the report. The pace and funding for a research program would then have to be carefully evaluated and planned in light of the currently unproven technologies involved, the potential benefits that may be gained, and current and evolving Government budget realities.

If you need further information related to this report, please contact the appropriate DOE Deputy Assistant Secretary for Congressional Liaison.

Yours sincerely,

Lake Barrett

Lake Barrett, Acting Director
Office of Civilian Radioactive
Waste Management

Enclosure

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A Roadmap for Developing ATW Technology: A Report to Congress

Foreword

In the Fiscal Year 1999 Energy and Water Appropriation Act, the U.S. Congress directed the Department of Energy (DOE) to study the accelerator transmutation of nuclear waste (ATW) and by the end of FY99 to prepare a "roadmap" for developing this technology. The Office of Civilian Radioactive Waste Management managed this task. To conduct the study and develop the report to Congress, DOE convened a steering committee, four technical working groups, and consulted with several individual international and national experts. The steering committee consisted of four members selected by DOE Principal Secretarial Officers (Defense Programs, Nuclear Energy, Science, and Civilian Radioactive Waste Management), three members selected by the Directors of Brookhaven, Argonne, and Los Alamos National Laboratories, and three members nominated by the National Academy of Sciences.

Roadmapping requires the acquisition and resolution of diverse points of view and alternatives from the beginning of the planning process. ATW technology roadmapping was completed in four phases, including the appointment of a steering committee and the convening of world experts on ATW technology. The experts provided the steering committee with information about the current status of ATW technology development, specialized areas in which additional research and development would be needed, and opportunities for international collaboration. This information was used to organize technical working groups, consisting of national laboratory and management and operations contractor personnel, and define their scopes of participation. The technical working groups subsequently provided reports containing detailed analyses of issues identified in workshops conducted during the second phase of roadmapping. The third phase consisted of providing the technical working group reports to the world experts for review and seeking their individual comments and recommendations for improvements in a concluding workshop. In the final phase of roadmapping, the technical working groups finalized their reports (this report and supporting documents are included on the attached CD-ROM) and the steering committee developed and reviewed this overview report for submission to Congress. The steering committee and chairs of the technical working groups achieved consensus for the recommendations expressed in this report after considering the comments and recommendations from the individual world experts and consultants.

This report contains a synthesis of information from worldwide experts, national laboratory staff, and individual consultants on developing ATW technologies. This process provided a broad and in-depth basis for their recommendations.

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Executive Summary

In the Fiscal Year 1999 Energy and Water Appropriation Act, the U.S. Congress directed the Department of Energy (DOE) to study the accelerator transmutation of waste (ATW) and by the end of fiscal year 1999 to prepare a "roadmap" for developing this technology. The DOE Office of Civilian Radioactive Waste Management managed this task.

In response to the congressional mandate, DOE developed, through the work of a steering committee and the national laboratories, an ATW roadmap that:

- Identifies the technical issues that must be resolved
- Proposes a schedule and program to resolve these issues
- Estimates the cost of such a program
- Proposes collaborative efforts with other countries and other programs developing ATW technology
- Identifies the institutional challenges of an ATW program
- Assesses the impact ATW technology could have on the civilian spent nuclear fuel program
- Identifies areas of development that could have benefits to other ongoing programs
- Estimates capital and operational life-cycle costs to treat spent fuel.

The products of each of these eight action items are:

1) **Six-year, science-based R&D program described to address the key technical issues.** The program would be capable of reducing the technical risk and assessing the technical viability of the ATW technology. The key technical issues identified are: a) lifetimes of proposed materials and components, b) reliability of components, c) degree of partitioning and separations, and d) quantification of long-lived radioactivity generated in operations, including spallation products.

2) **R&D plan to resolve issues developed and schedule identified.** Three years: complete systems and trade studies to justify major technical choices, complete an institutional analysis; five years: complete a preconceptual system design, complete a detailed research, development, and demonstration (RD&D) plan to begin after year six; at the end of six years, complete initial R&D and assess technical viability of ATW.

3) **Cost of six-year R&D estimated.** Total cost about $281M consisting of systems studies, $18M; accelerator R&D, $58M; separations R&D, $55M; target/blanket R&D, $123M; program management, $26M.

4) **Opportunities for collaboration identified.** Potential for active technical and financial collaboration with ongoing programs in Europe, Russia, and Asia.

5) **Institutional challenges identified.** Significant challenges for U.S. policies (e.g., nonproliferation of nuclear weapons and reprocessing), long-term program management commitments, long-term financing commitments, regulatory and environmental implementation, and public acceptance.

6) **Impacts on the civilian spent fuel program assessed.** Some impact of ATW, if successful, on the first repository program, could reduce potential long-term radiation doses from repository wastes by a factor of about 10; however, a repository is still required due to the presence of defense wastes, which are not readily

treatable by accelerator transmutation of waste, and the long-lived radioactivity generated by ATW operations. A reduced inventory of plutonium and other transuranics in the repository could decrease the likelihood of a future unauthorized attempt to recover fissile material.

7) **Benefits to ongoing programs identified.** Supportive to programs in nuclear nonproliferation, nuclear safety, waste management, high-power accelerators, nuclear chemical processes, nuclear fuels, next-generation nuclear fuel cycles, materials science, and nuclear technology in general.

8) **Capital and operational life-cycle costs to treat spent fuel estimated.** Total life-cycle cost to treat 87,000 tonnes (t) of commercial spent fuel: approximately $280B ($2B R&D, $9B demonstration, and $270B post-demonstration design, construction, operation, and decommissioning). Such a large upfront expenditure commitment will be a major challenge. Over the lifetime of ATW plant operations, much of the capital, operational, and development and demonstration (D&D) costs may be offset by the sale of electricity. However, when the time value of money is considered, this offset may be small. Total time: 117 years, of which R&D (initial 8 years) and demonstration comprise the first 27 years, and post-demonstration period activities comprise the following 90 years.

This report to Congress provides an overview of the study results, a roadmap for ATW technology development, and principal conclusions and recommendations. Additional details from the roadmapping effort are included on the CD-ROM provided with this report.

The "Back End of the Nuclear Fuel Cycle" — The Context for ATW

Nuclear reactors currently provide approximately 20% of U.S. electricity and 17% of the world's electricity; in some European countries, the nuclear share exceeds 80%. Nuclear energy use could grow in the next 50 years as developing countries increase their energy demand (estimates range from double to near ten times presently installed nuclear capacity).

The spent fuel discharged from U.S. reactors will reach 87,000 t by the time the existing U.S. nuclear plants reach the end of their license period. This discharged fuel contains 95% uranium (comparable to natural uranium), about 1% transuranic elements (principally plutonium), and radioactive fission products and activation elements. Most fission products lose their radioactivity within decades but a few (technetium and an isotope of iodine, for example) remain radioactive for many thousands of years and contribute to long-term repository waste management requirements.

Different countries take different approaches for management and use of discharged reactor fuel. England, France, Germany, Japan, and several other European countries recycle the fuel—plutonium is recovered and recharged into the current generation reactors for further energy production. In Russia, the discharged fuel is stored with the intent to enhance the energy potential of uranium and transuranics using breeder reactors. Transuranic elements also remain radioactive, some for hundreds of thousands of years. Japan also intends to use breeder reactors.

Canada, Sweden, the U.S., and several other countries employ a "once-through cycle" where the discharged fuel would be buried in a geologic repository.

A proposed geologic repository site at Yucca Mountain, Nevada, is currently being evaluated as to suitability for disposal of 63,000 t of commercial reactor spent fuel (containing approximately 600 t of plutonium and other transuranics and approximately 70 t of technetium and iodine); 4,300 t of defense high-level waste; and 2,700 t of DOE-owned fuel discharged from research, naval, and production reactor operations. (The 70,000 t total is the statutory limit for the first repository before obtaining a license for a second repository.) Under the current schedule, if the Yucca Mountain site is suitable, the U.S. repository program could license for construction by 2005 and be ready to start emplacing waste by 2010. These dates all are predicated on a decision on whether the site is suitable for development. That decision is expected in 2001. Loading of the repository with spent fuel, defense high-level waste, and DOE-owned fuel may be completed by 2035. The repository would be sealed about 100 years after loading is completed but may remain accessible for a longer time.

Partitioning/Transmutation and ATW

The schematic of an ATW system shown in Figure E.1 identifies the major components. As shown, a high-power particle accelerator produces energetic protons that react with a heavy metal target to produce neutrons. This target is situated at the center of a "blanket" region filled with assemblies containing chemically separated long-lived transuranic and fission product elements. The target and blanket assemblies together are called a transmuter. The fissionable transuranics are arranged such that neutron chain reactions cannot be sustained without the introduction of an external neutron source, which is provided by the accelerator. Thus, the transmuter is "driven" by the neutrons produced when the accelerated protons strike the target (this is called subcritical operation, which means that the accelerator protons are necessary to keep the transmuter running). The neutrons from the target, multiplied by neutrons from fissioning transuranics in the blanket, cause other

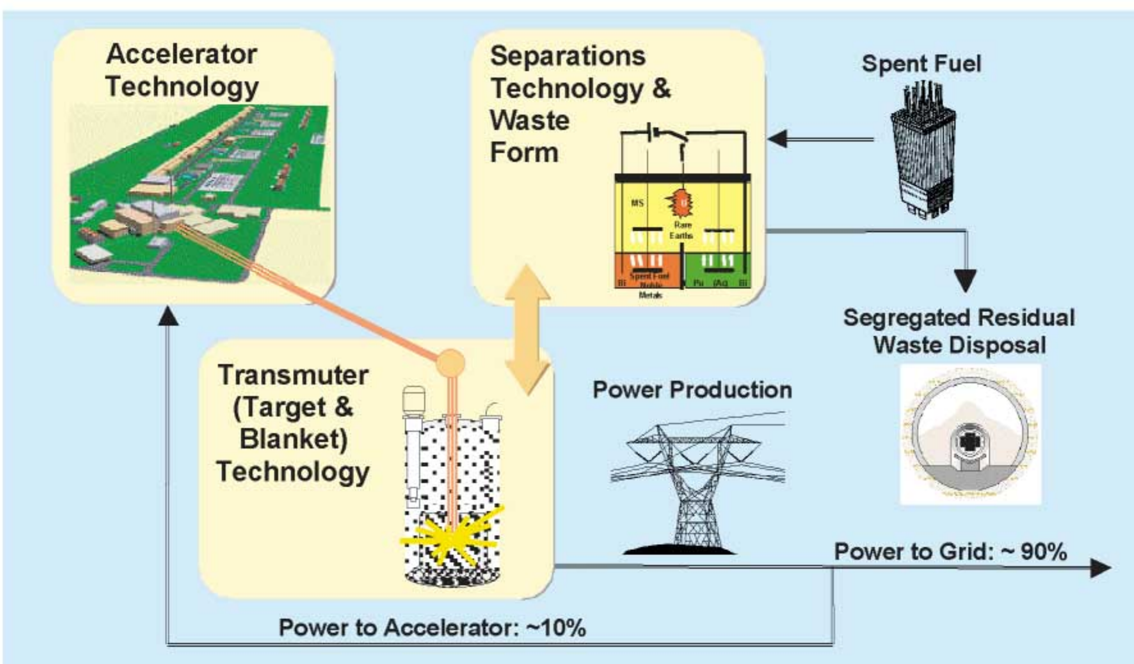

Figure E.1. Components of an ATW System transuranics to fission (releasing heat) and also transmute long-lived fission products into shorter-lived ones or stable products. Materials separations processes are used to prepare (partition) spent fuel for introduction into an ATW system; materials separations are also used within an ATW system for material recycle. Operation of an ATW system produces sizable amounts of heat that can be converted to electricity. Discharged products from an ATW system must be packaged in customized waste forms and disposed of as radioactive waste, or in the case of uranium, may be stored for possible future use.

The ATW system is also described as partitioning and transmutation. Partitioning means that materials of interest are chemically separated from the much larger mass of discharged reactor spent fuel and prepared for transmutation, recycle, and/or disposal. Transmutation means that nuclear processes are used on the transuranics and long-lived fission products from partitioning the spent fuel to achieve objectives of further energy recovery and/or creation of non-radioactive byproducts or shorter-lived byproducts to be emplaced in a repository.

Foreign efforts (described in more detail in Section 3) have been underway for some time in Europe (France, Italy, Spain), Russia (in part through International Science and Technology Center support), in Asia (Japan, Korea), and in other countries. These nations are pursuing ATW technology as a possible component of their long-term energy supply strategy. In the U.S., Los Alamos National Laboratory (LANL) has studied ATW technology since 1991 and has developed powerful accelerators for the Accelerator Production of Tritium program that are of the class proposed for ATW. Argonne National Laboratory (ANL) has developed partitioning technologies designed to retain self-protection of plutonium and transuranics at all times as part of the program of treating Experimental Breeder Reactor-II spent fuel for disposal.

Partitioning and transmutation was evaluated by a National Academy of Sciences (NAS) committee in 1991-1995. Their study concluded:

- Partitioning and transmutation of transuranic waste and certain long-lived radioisotopes in spent fuel is technically feasible and potentially beneficial to repository performance.
- A system to treat spent fuel in the U.S. would cost billions of dollars and require many decades to implement.
- Applying thermal and fast reactors to partitioning and transmutation would be based on considerable technological experience while ATW would require extensive development before technical feasibility could be realistically assessed.
- No partitioning and transmutation system offers sufficient promise to abandon the current once-through fuel cycle in the U.S. or to delay the opening of the first nuclear waste repository.
- A geologic repository would still be required even if a partitioning/transmutation system were introduced.
- Partitioning and transmutation may delay or eliminate the need for a second repository, but the capacity of the first repository could be increased through legislation or alternative technical avenues, such as not loading relatively short-lived isotopes like strontium-90 and cesium-137 into the repository until significant radioactive decay has occurred.

The NAS study considered concerns surrounding continued and growing global inventories of plutonium, as well as questions pertaining to the role of the U.S. in future nuclear science and fuel-cycle technologies. Significant improvements in the ATW system concept have renewed interest in partitioning and transmutation, and in ATW specifically.

The ATW Roadmap Process

To conduct the roadmap study, DOE convened a steering committee, four technical working groups, and a panel of national and international experts associated with development of ATW technologies. The steering committee consisted of representatives from four DOE Program Offices (Office of Nuclear Energy, Science and Technology; Office of Science; Office of Defense Programs; Office of Civilian Radioactive Waste Management) with technical interest in ATW, a representative from each of the Directors of ANL, Brookhaven National Laboratory (BNL), and LANL, and three members nominated by the NAS. The four technical working groups were created to focus on systems scenarios and integration, the accelerator, the target and blanket system, and materials separations. These groups included scientists and engineers from 12 national laboratories and facilities currently involved in related research activities. Pacific Northwest National Laboratory provided administrative support for the roadmapping activities and developed the estimated life-cycle costs for the postulated ATW System.

Major Technical Issues

The roadmap activities and world experts' meetings identified the following principal technical issues to be addressed in the R&D phase. They will be significant challenges during the initial R&D program and if solutions are found, must be proven in a demonstration phase.

- Lifetimes of proposed materials and components in the radiation, thermal, and chemical environments of ATW
- Operational reliability and availability of the ATW system
- Operational safety of an ATW system consistent with regulatory requirements
- Degree of partitioning separation achievable for uranium, transuranics, and long-lived fission product elements from discharged commercial reactor fuel and spent ATW fuel assemblies
- Quantification of long-lived radioactivity generated in ATW operations including spallation products, and the implications for waste streams and waste forms.

The ATW Roadmap — A Science-Based, Technical-Risk-Reduction Program

The steering committee concluded, consistent with the advice of individual world experts, that an initial six-year program of trade studies and science-based R&D on key technology issues would be prudent to increase the knowledge base to support future decisions. The recommendations of the steering committee, therefore, pertain to an initial science-based program conducted with international collaboration that includes attention to global issues of nonproliferation, ecology, energy, and economics.

Because the issues addressed by ATW are global (current and future energy needs and options, weapons nonproliferation, management of radioactive waste), cooperation/collaboration within the international community would be beneficial to all parties. Collaboration would help ensure an effective use of resources in evaluating options, increasing the knowledge base, and reducing technical risks.

A panel of world experts from several countries with interests in ATW (France, Italy, Japan, Russia, Sweden, and the U.S.) was an integral part of the process to include international perspectives and identify areas of mutual interest/benefit. Synergies have been identified between an ATW program in the U.S. and ongoing international activities. Many opportunities exist for technology partnerships that would contribute to the success of a U.S. ATW R&D program when technical, cost, and schedule issues are considered. The prime objective would be demonstration of the scientific feasibility of relevant technologies, independent of the specific national ATW configuration or application. Access to international facilities/capabilities could partially compensate for gaps in the present U.S. infrastructure (e.g., fast spectrum irradiation capabilities). Such participation would keep the U.S. in contact with worldwide developments in nuclear technology and help preserve U.S. influence in nuclear issues.

Key elements of the collaborative efforts could include U.S. participation in:

- Systems/trade studies (motivation/rationale, options, scenarios).
- Science-based R&D activities, e.g., basic nuclear data, studies of basic technologies (fuels, coolants, materials, etc.). One specific focus of these efforts would be fundamental studies on lead-bismuth eutectic coolant and target technology and the associated materials compatibility issues.
- Potential for future demonstration experiments and/or dedicated facilities. The cost of such facilities and their operations provides considerable impetus for multinational collaboration.

The science-based technical risk-reduction program is illustrated in Figure E.2. It integrates trade studies aimed at optimizing the ATW system technical approach and configuration with focused R&D efforts aimed at the preferred technology choices. These science and technology efforts:

- Confirm the performance regime for those technologies that are based on extrapolation of well-understood technologies.
- Indicate the likely feasibility of those attractive, but not yet proven, technologies.
- Focus on achieving early results impacting key issues; for example, accelerator reliability, fuel forms, and lead-bismuth/structural steel compatibility under irradiation. Loop tests could be performed in the Fast Flux Test Facility (FFTF), should FFTF become available.
- Begin analysis of institutional issues and public involvement strategies.

Table E.1 shows the components and estimated costs associated with the recommended initial six-year science-based technical risk reduction R&D effort.

The science-based approach:

- Prioritizes research and addresses key areas.
- Provides flexibility in future decision-making for system definition and development.
- Delays policy decisions on the costly demonstration phase until more complete technical data are available.

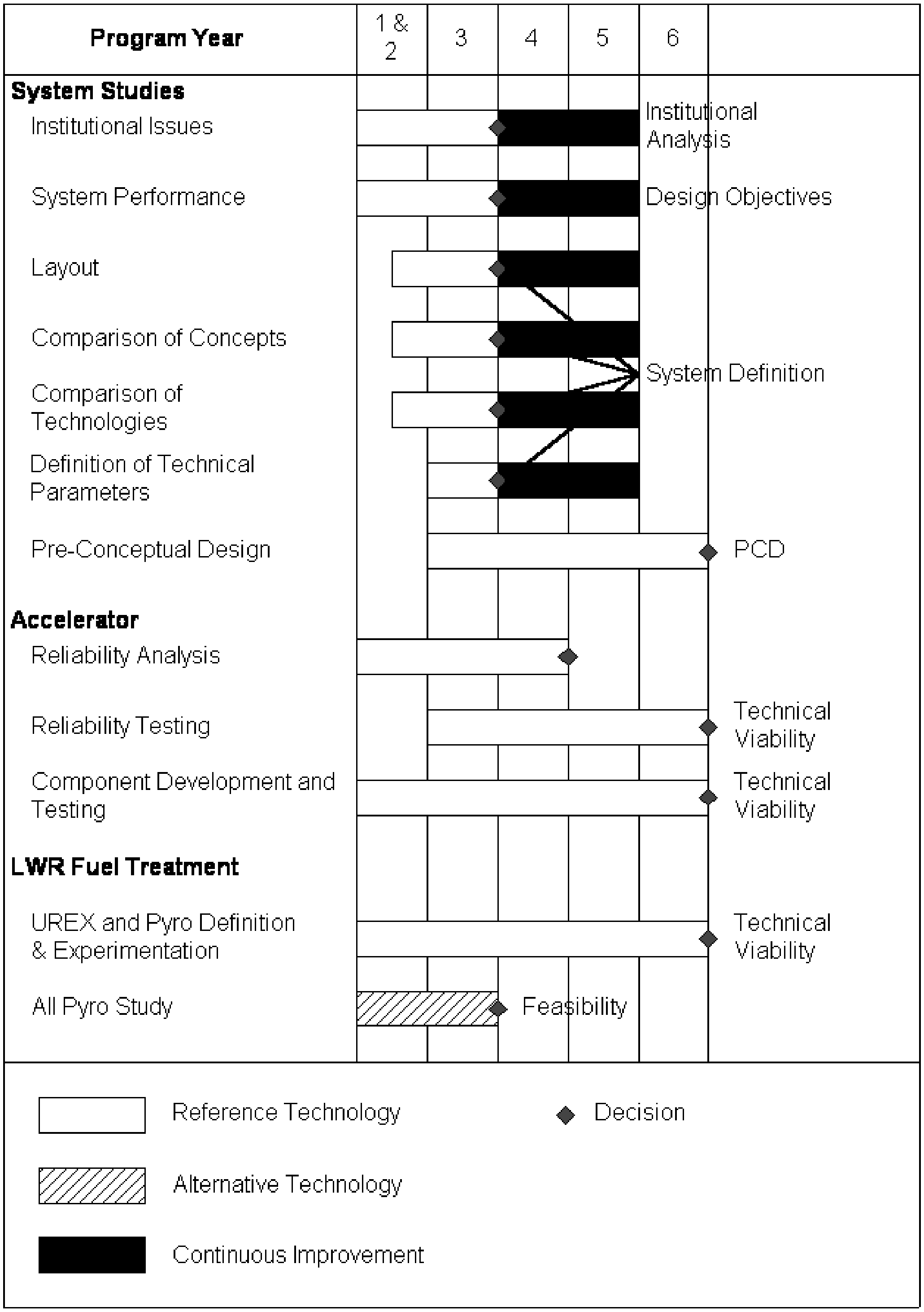

Figure E.2. A Six-Year Science-Based Program Roadmap

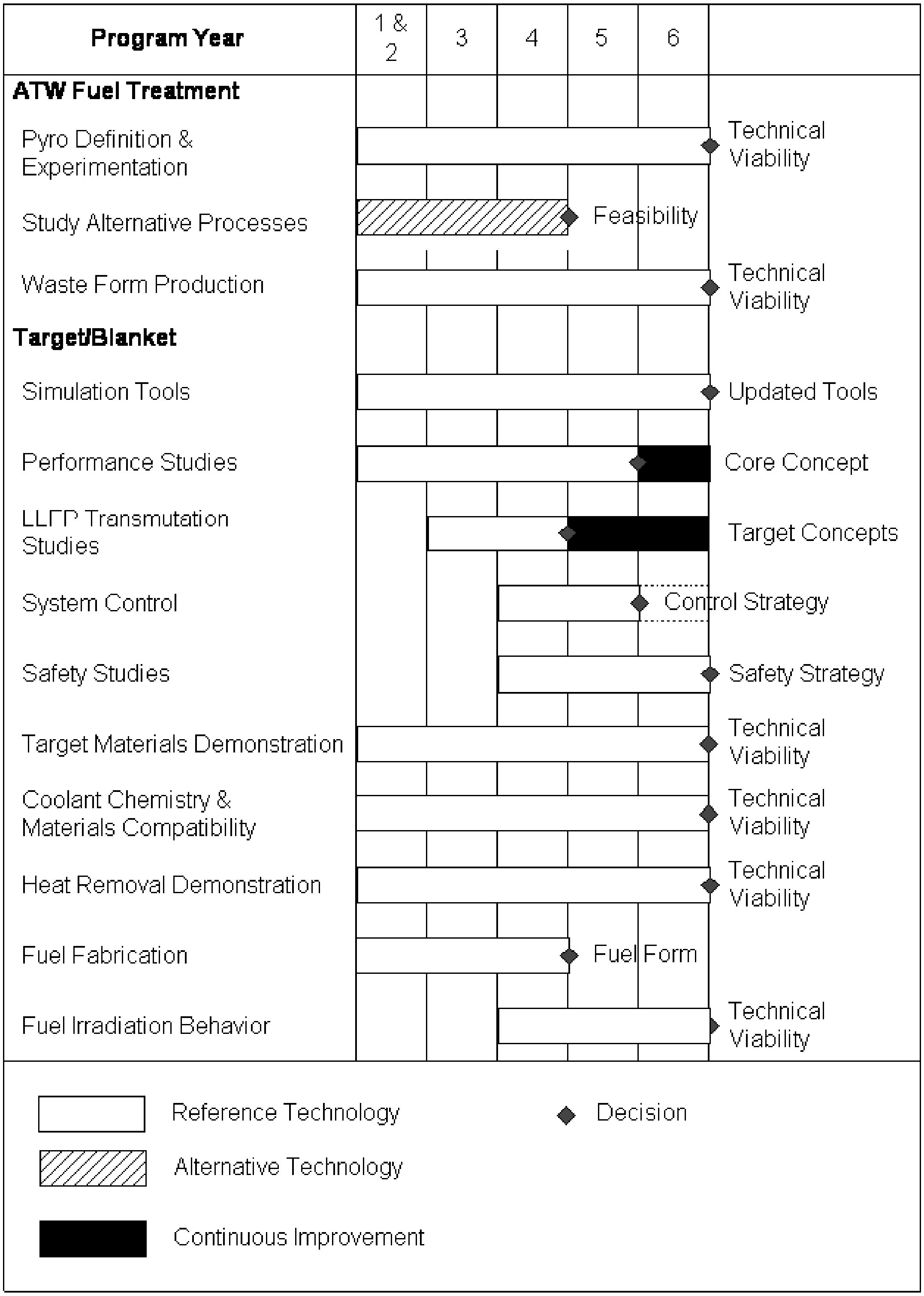

Figure E.2. (Continued) A Six-Year Science-Based Program Roadmap

Table E.1. Estimated Costs for the Six-Year R&D Program for ATW Technologies (Millions of 1999 Dollars)

Program Year	1 & 2	3	4	5	6	Total
System Studies	4.5	6.5	3.0	2.0	2.0	18.0
Accelerator Development	6.5	12.0	16.0	13.5	10.0	58.0
Separations and Waste Forms	5.4	8.2	12.6	15.3	14.0	55.5
Target and Blanket	10.8	12.8	36.4	37.0	26.5	123.5
Program Management	3.0	4.0	6.0	7.0	6.0	26.0
Total	**30.2**	**43.5**	**74.0**	**74.8**	**58.5**	**281.0**

A Deployment-Driven ATW Roadmap

In compliance with the congressional mandate and on the basis of current knowledge, a deployment-driven roadmap for research and development, prototype, demonstration, and implementation phases of an ATW-based system to treat 87,000 t of spent fuel also has been produced, and a cost for each phase of the campaign has been estimated. This effort focused on the portion of the congressional request related to:

- Assessment of the impact ATW technology could have on spent fuel from U. S. power reactors
- Identification of the technical issues that must be resolved and a schedule and program to resolve them (including program costs)
- Estimation of capital and life-cycle costs to treat spent fuel.

This roadmap study was based on deployment of a system of ATW stations that were assumed to meet assured design requirements of 99.9% destruction of transuranics, 99.9% recovery of uranium, and 95% transmutation of technetium-99 and iodine-131. The radiological risk of a nuclear facility to people and the environment is expressed by a calculated radiation dose rate at a specified distance from the facility at various times subsequent to emplacement of radioactive material in the facility. With these assumptions, partitioning and transmutation of spent fuel could reduce its contribution to the effective dose from a repository at Yucca Mountain by a factor of about 1,000. However, the overall peak dose at a respository would be reduced by a factor of only ten because the presence of defense waste and DOE spent fuels (neither treated by ATW) would then dominate the total dose. Under the present repository emplacement scenario, these dose reductions are based on the current understanding of repository performance at the proposed Yucca Mountain site.

The associated revenue from electricity sales could be worth as much as $300B—revenue that could be used as partial offset to the large costs of the development and deployment of ATW technology. As reported in the supporting cost report to this report, there is a low probability that the cost of generating ATW electricity would be lower than the production costs of most of the investor-owned utilities in the U.S. Therefore, ATW power sales are unlikely to fully recover production costs. The inventory of plutonium and other transuranics chemically separated from spent fuel would be reduced by a factor of 1,000 to less than 1 t at the end of ATW operations.

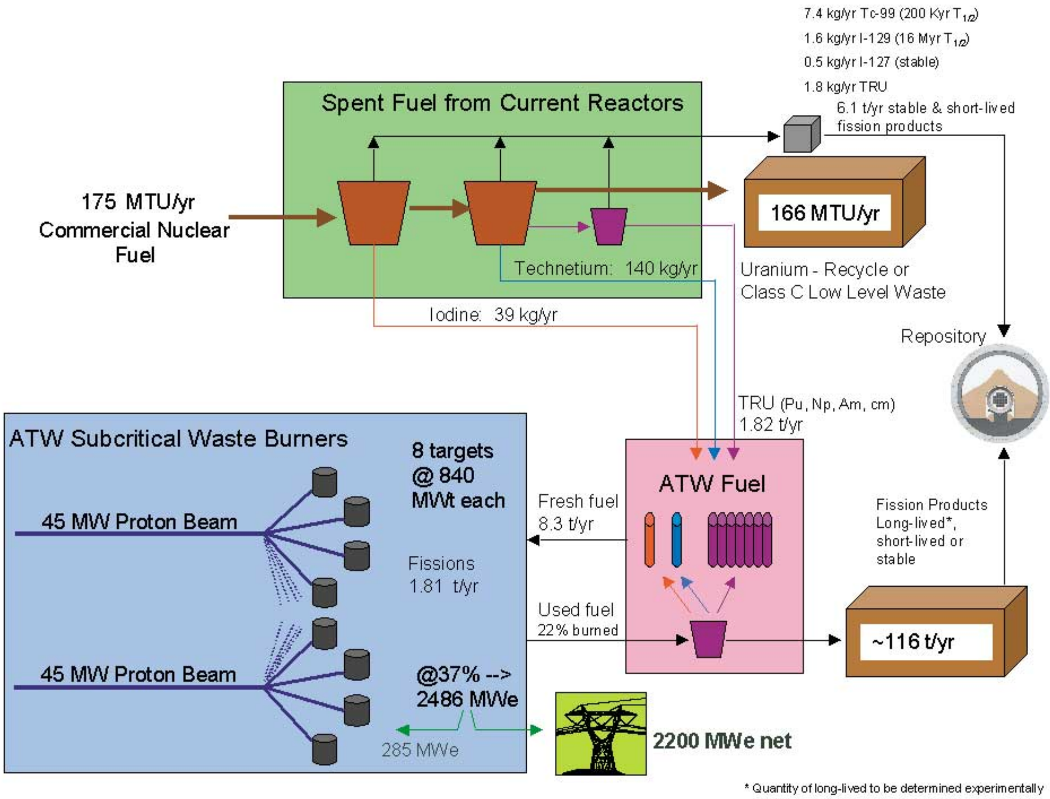

Figure E.3. Annual Equilibrium Operation of a Conceptual ATW Station Based on Average Composition of Deployment-Driven Scenario Spent Fuel

To estimate both system demonstration and life-cycle costs for ATW, it was necessary to create a scenario for development and deployment. The scenario that provides the basis for life-cycle costs is based on the following assumptions about the next several decades:

- ATW is developed rapidly to achieve the earliest possible implementation (institutional delays are minimal).
- No new reactors are built and no license extension occurs.
- ATW units are built and operated over a total period of about 90 years to partition and transmute 87,000 t spent fuel.
- Costing data were generated using nuclear technology available today, for which a suitable level of costing experience at prototype, demonstration, and/or deployment stages has been accumulated.

These assumptions provided a defined basis for the scope of fuel to be treated and for the time sequencing of the ATW development, demonstration, and deployment. The annual operation for an ATW station under the deployment-driven scenario is given in Figure E.3.

If begun early in the twenty-first century, the development of a proven system could be achieved under optimistic conditions by approximately 2035. The up-front costs of R&D, prototype, and research and demonstration phases would total about $11B.

A campaign to partition and transmute a spent fuel inventory of 87,000 t using a reasonably sized deployment of eight ATW installations, each generating approximately 2200 MW (net) of electricity, would take until approximately 2110. Capital costs for each of the eight deployed ATW installations would be from \$6B to \$7B. Annual operating costs (including debt servicing) would be about \$500M. Much of the capital, operational, and D&D costs may be offset by the sale of electricity.

The societal decision to proceed with deployment would require resolving a number of issues. Significant among these is interpretation of the U.S. policy concerning reprocessing as applied to ATW, interpretation of facility siting and licensing regulations as applied to accelerator driven systems, sale of the electricity in the deregulated commercial marketplace, and public acceptance.

Technical activities for the first eight years of a deployment-driven scenario would address the key technical issues for each ATW element: accelerator, target, nuclear blanket system, materials separations, and waste forms. Key decisions to be made during this aggressive eight-year phase would be:

- Determination of ATW technology feasibility.
- Selection of ATW target materials, waste form, fuel form, and coolant.
- Selection of spent fuel reference processes.
- Selection of accelerator components and definition of linac reliability.
- Selection of an ATW demonstration system scenario.

The initial R&D phase would be followed by a sequenced demonstration phase having the following milestones:

- **Year 15:** Demonstration comprising a full-energy, reduced power (reduced current) accelerator, a full-sized neutron target, and a small transmuter generating 30 MWt (about 1/30th of full scale).
- **Year 23:** Demonstration facility upgraded to full accelerator power and a transmuter operating at a thermal power of one-half the final (840 MWt) module size. Processing and fuel-fabrication facilities would be operational.
- **Year 29:** Demonstration facility upgraded to two transmuter modules at full power producing electricity; full-scale processing and fuel fabrication facilities operational.

Conclusions from the ATW Roadmap Study

Conclusion 1: A repository is an essential element of the nuclear fuel cycle with or without ATW deployment. It is required in the U.S. for disposal of defense high-level waste, DOE-owned spent fuel, and civilian spent fuel.

Conclusion 2: Applying an ATW system to commercial civilian spent fuel as described in this report, would reduce its contribution to the dose predicted in the total system performance analysis for the Yucca Mountain repository project. The defense high-level waste and DOE-owned spent fuel contents of the repository would then dominate long-term dose, and predicted peak doses would be reduced by a factor of ten. The inventory of fissionable materials from commercial spent fuel in the repository could be reduced by a factor of 1,000. The volume of waste packages associated with commercial spent fuel would be slightly reduced. The 82,000 t of chemically separated uranium could be suitable for near-surface disposal at a low-level waste site or non-shielded storage for potential future use in advanced reactors.

Conclusion 3: For a deployment-driven R&D and development schedule, a program resulting in a near full-scale prototype to demonstrate the ability to deploy an ATW system would require approximately

20 years and cost about $11B. Public acceptance as well as several other complex institutional issues would have to be addressed in the process leading to a decision for deployment.

Conclusion 4: The roadmap developed for deployment of ATW systems for partitioning/transmuting of commercial spent fuel depends on implementation scenarios that were assumed for decades into the future, and it therefore has large uncertainties. For the aggressive implementation scenario assumed in the roadmap study, several decades and several tens of billions of dollars will be required; the scale of energy recovered and its value in the marketplace is comparable to that of large power plants currently operating. Much of the capital, operational, and D&D costs may be offset by the sale of electricity.

Conclusion 5: Auxiliary benefits would be derived from development of ATW technology. Among them is the opportunity to participate in and influence international efforts in areas of nuclear nonproliferation, safety, and waste management.

Conclusion 6: Active participation by the U.S. in international ATW R&D efforts could have positive impacts on cost and schedule for U.S. ATW programs and may provide access to facilities/capabilities not available in the U.S. Countries pursuing ATW-type programs or technologies are shown in Figure E.4 (detailed in Section 3.0, International Cooperation and Collaboration).

Conclusion 7: Although no "show stoppers" are identified, a several-year science- and technology-based R&D program would be prudent to increase the knowledge base needed for ATW. Such a program would likely provide additional benefits in related technologies (e.g., materials science, accelerators, etc.).

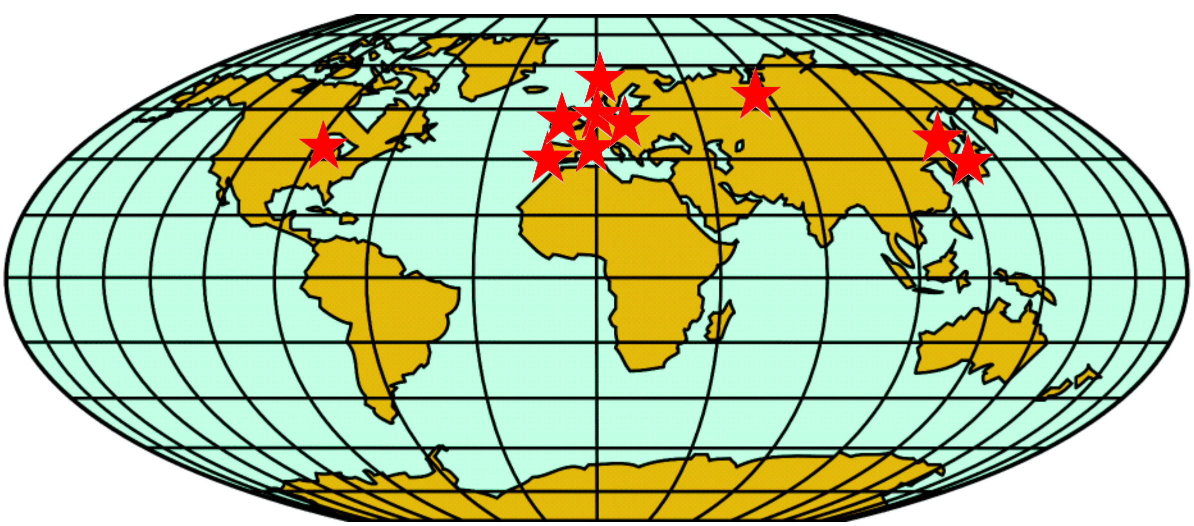

Figure E.4. Countries Pursuing ATW-Type Programs or Technologies

ATW Roadmap Study Recommendations

The Administration makes no recommendation with regard to the panel's proposed research program. Should there be a national policy decision to pursue this technology, the expert group has identified a science-based research program to address the technical issues cited in the report. The pace and funding for a research program would then have to be carefully evaluated and planned in light of the currently unproven technologies involved, the potential benefits that may be gained, and current and evolving Government budget realities.

An initial science and technology development pathway involving international collaboration is recommended by the ATW Steering Committee.

Recommendation 1: An initial period of up to six years should be undertaken for trade and system studies, for two distinct purposes. The first would be to evaluate ATW within the framework of nonproliferation, waste management, and economic considerations. The second would be to evaluate the efficacy of the numerous technical options for ATW system configuration, trading off such factors as accelerator type and power, size (heat rating) of each transmuter module, the neutron spectrum characteristics and effectiveness for transmutation, type of nuclear fuel and coolant, technologies for materials separation under proliferation-resistant conditions, etc. These trade and system studies would refine the goals and requirements for an ATW system.

Recommendation 2: During the six-year period, science-based R&D should address the key technology issues identified during the roadmap preparation for each of the system elements (partitioning, recycle, accelerator, spallation target, and transmuter), identified in Section 2 of this Report to Congress. Special attention should be directed to the high-priority issues identified earlier. The science-based R&D and trade studies should support each other mutually, e.g., establishing feasibility and identifying other options.

Recommendation 3: Recognizing existing programs in Europe and Japan, the above recommendations should be undertaken in the form of strong international collaboration at the level of system studies, system configuration, and on science-based R&D. After establishing technology preferences, opportunities for collaboration on international ATW technology-demonstration efforts should be explored.

Recommendation 4: A total funding level of approximately $281M is needed for support of the initial six-year science- and technology-based R&D program. This level will allow deliverables projected for the six-year program to be met.

Recommendation 5: At the end of the fifth year or the beginning of the sixth year of an initial R&D program as described in Table E.1, the program would be able to prepare for Congress the following deliverables:

- A reference ATW system definition at a preconceptual level.
- A description of the status of ongoing science and technology efforts highlighting major interim results and needs.
- A development and demonstration plan for ATW including further use of existing U.S. and/or international facilities and identification of demonstration facilities to be constructed.
- A preliminary design and cost for such demonstration.
- Institutional analysis defining the strategy for addressing and dealing constructively with issues such as regulation, public acceptance, etc.

Next Steps

The Fiscal Year 2000 Congressional appropriation provides funding for research on ATW. The funds are included in the appropriation to the Office of Nuclear Energy, Science and Technology.

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1.0 Background and Introduction

In the Fiscal Year 1999 Energy and Water Appropriation Act, the U.S. Congress directed the Department of Energy (DOE) to study the accelerator transmutation of waste (ATW) and by the end of fiscal year 1999 to prepare a "roadmap" for developing this technology. The Office of Civilian Radioactive Waste Management managed this task. This report provides an overview of the study results and the roadmap for developing ATW technology. To conduct the study, DOE convened a steering committee, four technical working groups (TWGs) for specific functions, and a panel of international experts associated with development of ATW technologies, as shown in Figure 1.1. The steering committee consisted of representatives of the Directors of four DOE Program Offices with technical interests in ATW, representatives of the Directors of Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), and Los Alamos National Laboratory (LANL), and three members nominated by the National Academy of Sciences (NAS). The panel of world experts consisted of 13 national and international leaders in ATW technology programs. The four TWGs were composed of scientists and engineers from 12 national laboratories and facilities currently involved in related research activities.

The congressional mandate gave clear direction on the scope of the roadmapping effort and the content of the required report:

"...to conduct a study of accelerator transmutation of waste (ATW) technology. The Department is to establish, in coordination with its laboratories, a roadmap for the development of ATW technology. The roadmap should identify the technical issues that must be resolved, a proposed time schedule and program to resolve these issues, and the estimated cost of such a program. The roadmap should also consider and propose collaborative efforts with other countries developing ATW technology and

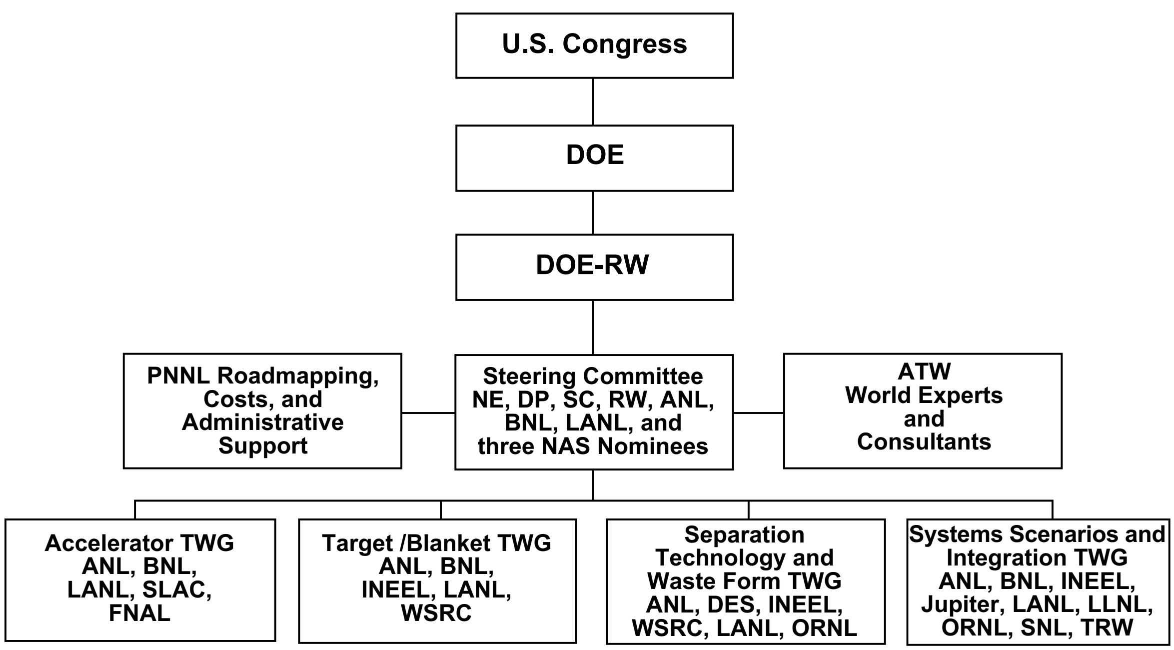

Figure 1.1. ATW Project Organization Chart

other programs developing accelerator technology. In addition, the report should include an assessment of the institutional challenges of this program, the impact this technology could have on the civilian spent nuclear fuel program, areas of development which could have benefits to other ongoing programs, and the estimated capital and operational life cycle costs to treat civilian spent nuclear fuel."

Roadmapping differs from conventional program planning activities in that it brings together a number of diverse points of view from the beginning of the planning process. The ATW technology roadmapping was completed in four phases including the appointment of a steering committee to guide the effort and the convening of world experts. The experts discussed the current status of ATW technology development, the specialized areas in which additional research and development (R&D) would be needed, and opportunities for international collaboration. This information was used to organize the TWGs and to define their scopes of participation. The TWGs subsequently provided reports containing detailed analyses of issues identified in workshops conducted during the second phase.

The third phase consisted of providing the TWG reports to the world experts for review and seeking their individual recommendations for improvement in a concluding workshop. In the final phase, this overview report and the supporting TWG reports were completed, reviewed, and prepared for submission to Congress.

Complete details of the roadmapping effort, life-cycle cost analysis, and the final TWG technical reports are contained on the CD-ROM provided with this report.

1.1 Why Treat Spent Fuel?

The final disposition of spent fuel has been, and continues to be, an issue of national and international importance. In the United States, where power reactors operate on a once-through fuel cycle, spent fuel is treated as a waste product. A program is ongoing to characterize a candidate site at Yucca Mountain, Nevada, for a permanent geologic repository for spent fuel and high-level waste (HLW). This potential repository site is being sized to safely dispose of 63,000 tonnes (t) of spent fuel from nuclear power reactors and 7,000 t of spent fuel and HLW from DOE operations. Commercial power reactors in the United States currently discharge about 2,000 t of spent fuel annually.

After spending a certain time in a reactor, the fresh fuel (primarily composed of uranium) becomes spent fuel and is removed from the reactor. During reactor operations some of the uranium is fissioned, producing fission products, and some uranium absorbs neutrons, generating activation products. Some of the activation products become transuranics (TRU) such as plutonium and other actinides. Spent fuel is removed from these reactors when its reactivity has decreased due to the buildup of fission and activation products, and because the mechanical integrity of the fuel has been reduced. Thus, spent fuel is not "spent" in the sense that all its energy has been completely extracted.

At the time it is removed from the reactor, most of the radioactivity in spent fuel is from the fission products cesium-137, strontium-90, and other products that have relatively short half-lives (tens of years). These short-lived fission products can be readily retained in storage facilities for reasonable periods to minimize their threat to the human environment. The major constituent, uranium, can be separated and may be disposed of as low-level radioactive waste or may be retained for possible future use.

In addition to the uranium and short-lived fission products, spent fuel contains plutonium, other actinides, and other fission products that have half-lives of thousands to millions of years. The treatment of spent fuel to deal with these constituents (i.e., separation and transmutation to more benign forms) could enhance future repository performance.

By removing and transmuting the plutonium, other actinides, and some of the long-lived fission products from spent fuel, the following results could be achieved:

- The 600 t of plutonium that would otherwise be in the repository would no longer be available for potential future use.
- The residual energy content of the uranium and actinides could be extracted in power reactors. The actinides alone have an energy content equivalent to 30% of the energy released by fission during generation of the spent fuel. The remaining uranium has a very large residual energy content—about two orders of magnitude higher than the energy released during fission.
- Performance of the repository may be improved by reducing the inventory of some of the long-lived radionuclides.

1.2 Ways of Treating Spent Fuel

Several processes to treat spent fuel are currently being used by various countries. These processes range from packaging fuel elements for long-term storage or disposal, to complex chemical processing to separate some components and then treating and packaging other components before long-term storage or disposal.

Processes currently in use include:

- Packaging spent fuel and placing it in long-term storage.
- Separating plutonium and mixing it with uranium to form new fuel for light-water reactors (LWR) (thermal neutron spectra) or liquid-metal-cooled reactors (fast neutron spectra).

Processes being explored include:

- Separating plutonium and other actinides, forming these materials into fuel, and transmuting in critical reactors.
- Separating plutonium and other actinides, forming these materials into fuel, and transmuting in accelerator-driven systems (ATW).
- Separating plutonium and other actinides, forming these materials into fuel, and transmuting in fusion based systems.

All processes involving transmutation of plutonium and other actinides result in the release of thermal energy that can be converted into electricity.

1.3 What is Transmutation?

Transmutation can be defined as the transformation of one isotope into another isotope by changing its nuclear structure. In the context of conditioning the constituents of spent fuel, transmutation converts plutonium and other actinides and long-lived fission isotopes into isotopes with more favorable characteristics.

Two examples of nuclear transmutation from exposure of isotopes to neutrons are neutron-induced fission and neutron capture (see Figure 1.2). Conversion of fresh fuel to spent fuel in a nuclear reactor represents a transmutation process in which materials are exposed to neutrons. Neutron exposure (and the resultant transmutation) can be achieved in a nuclear reactor (a system designed to maintain a steady level of neutrons in a self-sustaining configuration) or in an accelerator-driven subcritical system. In the latter, neutrons result when an accelerator beam of high-energy particles (protons, for example) collides with a dense, high-atomic-number target (this reaction and the resulting particles are referred to as "spallation"). These neutrons are then multiplied through interactions with fuel materials in a surrounding blanket arrangement. In either case, the exposure of materials to neutrons results in their transmutation.

1.4 History and Benefits of Accelerator-Driven Systems

Several countries have considered using accelerator-driven transmutation systems for treating spent fuel and generating power. These systems are generally referred to as accelerator-driven systems (ADS) or accelerator-driven transmutation technologies (ADTT). Some of these options are described in Section 2 of this report, and more detail on international programs is provided in Section 3.

In the United States, using ATW for treating spent fuel was compared with treatment by thermal and fast reactors in an extensive study the National Academy of Sciences (NAS) Separations Technology and Transmutation Systems (STATS) committee performed for DOE in 1991-1995. The committee concluded that separation and transmutation of minor actinides and certain long-lived radioisotopes in spent fuel is technically feasible and potentially beneficial to repository performance. Since that study, considerable work has been conducted on the enhancement of high-energy accelerators such as those that would be used for ATW. The National Research Council also observed that applying thermal and fast reactors to separation and transmutation would be based on considerable technological experience while ADS would require extensive development before even technical feasibility could be realistically assessed.

LANL began studying ATW in 1991 and, as part of the present study, proposed an ATW technical approach. In this approach, spent fuel would be processed for the removal of uranium and the separation of long-lived radionuclides, principally plutonium, neptunium, americium, curium, technetium, and iodine. These separation products would be manufactured into fuel or transmutation assemblies. The assemblies would be placed into a transmuter and transmuted. The transmuter facility would use an accelerator-driven target/blanket assembly to produce large numbers of neutrons that cause the transmutations. The

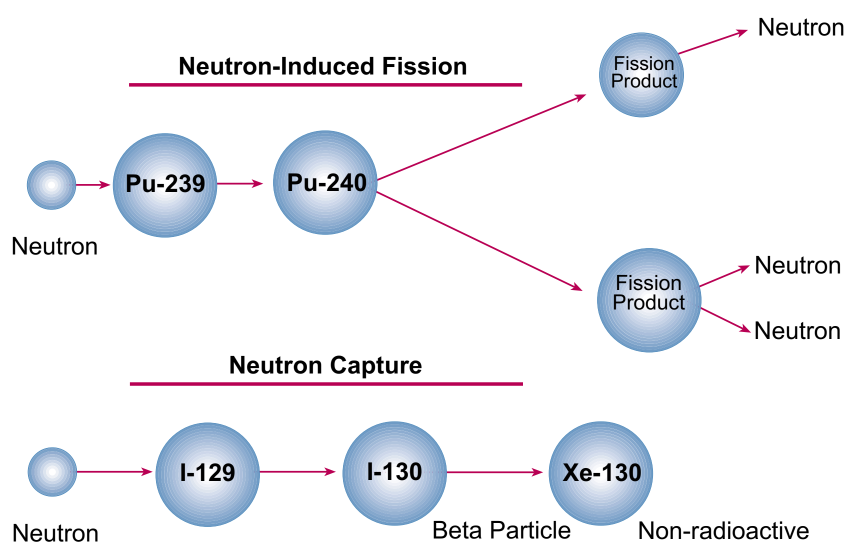

Figure 1.2. Two Examples of Transmutation

waste from these processes would then be incorporated into forms acceptable for disposal. The excess thermal energy from the transmuter would be used to generate electrical power. This approach was reviewed in January 1998 by the Massachusetts Institute of Technology (MIT), which found no insurmountable issues or show stoppers: "While the proposed technologies are, in several instances, extrapolations of existing experience to untested conditions, they represent reasonable targets for development in the next 5 to 10 years." The LANL-proposed design provided part of the basis for the ATW roadmapping process and the estimates of total cost to process spent fuel.

Potential Benefits

- A factor of 10 improvement in repository performance.
- Repository design flexibility.
- Decreased waste volume.
- Electrical energy production.
- Reduced risk of proliferation or diversion of nuclear materials.
- Source of isotopes for medical, industrial, and research purposes.
- Potential to generate significantly larger fluxes of neutrons than currently possible with critial reactor sources or pure spallation sources.
- Potential to provide a source of neutrinos that may help answer some of the fundamental questions of science.
- Global improvements in radioactive waste management and, through a possible expansion of nuclear power, reduced pollution from fossil fuel usage.
- Opportunities for international collaboration and participation in other ADS programs.
- Potential to assist DOE in its mandate to maintain core competency in nuclear technologies of national security interest.

1.5 The Components of ATW

The ATW components are 1) a linear accelerator that can deliver a high-energy (1 GeV) proton beam at high beam power, 2) a transmuter consisting of a target/blanket in which spallation reactions convert the proton beam into an intense neutron flux for the transmutations, and 3) chemical processes for treating spent fuel to separate long-lived radioactive isotopes and actinides for initial and recycle irradiation (see Figure 1.3).

Accelerator

A linear accelerator has many desirable features because of the high beam power requirements. Linear accelerators are believed to be capable of accelerating over 100 mA of protons to several GeV, implying that continuous beams in the few hundred-megawatt range are practical. The other main option for high-power beams, cyclotrons, are limited to maximum energies of about 1 GeV and electric currents of a few mA. Cyclotrons appear to be fundamentally limited to a few megawatts of beam power, which may suffice to drive energy amplifier thorium-based systems (proposed in Europe) but may be insufficient for the currently envisioned U.S. application.

Transmuter (Target/Blanket Assembly)

A fast neutron spectrum has advantages for transmutation for two reasons. First, nearly all actinides will fission in a fast neutron spectrum, giving maximum efficiency for destroying plutonium and other actinides. Second, the fast spectrum will produce an excess of neutrons that, when moderated, may be used to transmute long-lived fission products (technetium and iodine, for example). A liquid metal coolant is generally chosen for satisfactory fast spectrum operation. Liquid lead-bismuth eutectic (LBE) is attractive as both the spallation target (neutron source) and the coolant for the specific ATW application. Because of its extensive and international experience basis and the underlying similarities with LBE, sodium is also a possible coolant.

A metal fuel is generally chosen to provide the high rates of heat transfer required. It would have a different composition than traditional metal fuels (75 wt% zirconium as compared to less than 10 wt% for advanced liquid metal reactors). Use of a metal fuel makes pyrometallurgical processing attractive for recovery and recycle of the discharged ATW fuel.

Structural materials and cladding must be compatible with the selected coolant. Russian structural materials developed for LBE applications will need to be evaluated and tested in the United States. On the other hand, sodium-compatible materials are available and would meet the requirements for ATW systems utilizing sodium as the coolant.

Chemical Processes (Separations)

In selecting a separation technology, generally two primary options exist: comparatively well-known aqueous separations versus pyrometallurgical separations that provide some advantages for ATW. Because of its capacity for high throughput and its ability to provide a uranium stream that meets Class C low-level waste requirements, an aqueous process, "UREX," was chosen as the reference technology for processing spent fuel. Processing of spent LWR fuel using pyrometallurgical separation methods will be evaluated to determine if they offer advantages over the aqueous UREX process.

After initial separation of uranium, all further ATW separations and processing steps are based on pyrometallurgical processing. The pyrometallurgical separations provide greater proliferation resistance, and the

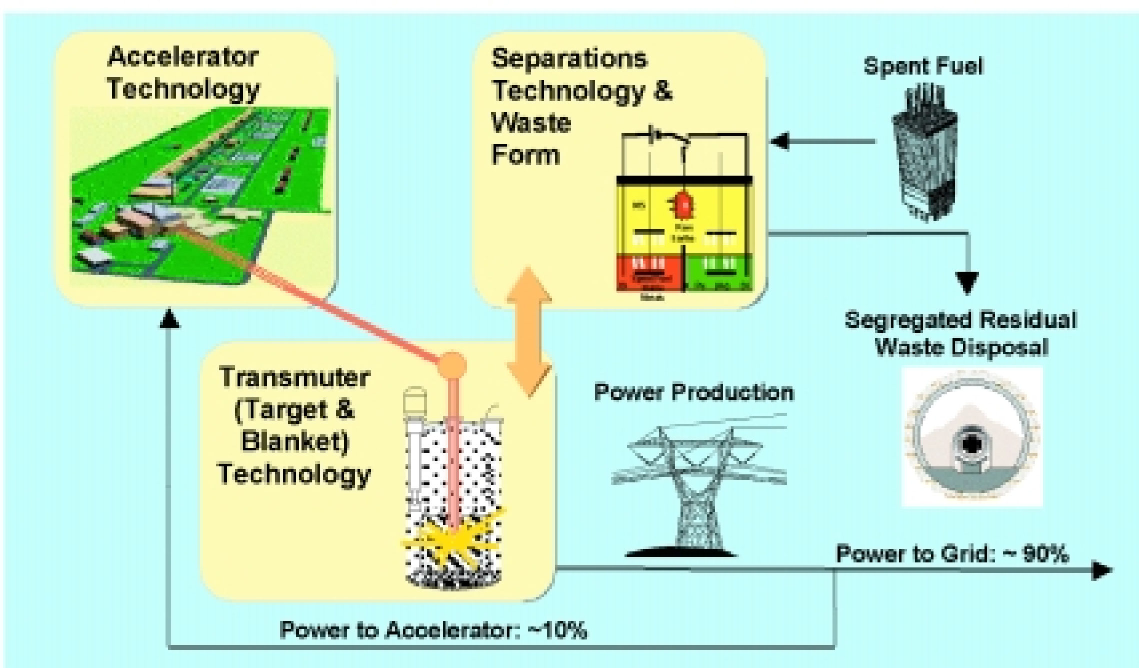

Figure 1.3. Components of an ATW System

pyroprocess would be more capable of withstanding the high heat and radiation anticipated during the processing of fuel that has been irradiated in the ATW transmuter. All separations, either aqueous or pyro-based, should be modularized and constructed close to the transmuter, thereby limiting materials transport to either spent fuel from a respository or current nuclear power reactors or waste forms from ATW stations.

1.6 Major ATW Research and Development Issues

The development and demonstration of ATW technology will require the consideration and resolution of a number of issues. This report, while identifying many key issues, addresses only those issues associated with research, development, and demonstration (RD&D). Key schedule issues addressed in the roadmap are the milestones for critical decisions concerning the feasibility of the technology and how these decisions affect the demonstration of an ATW system.

ATW technology has matured in the past several years from activities in related programs such as Accelerator Production of Tritium (APT), Spallation Neutron Source (SNS), and activities conducted in other countries, notably France, Italy, Japan, Russia, and Spain. The APT program being conducted at LANL and other DOE sites has progressed to preliminary facility and equipment design and testing of components and devices. The SNS program being conducted at Oak Ridge National Laboratory (ORNL) and other national laboratories has progressed to the stage of facility and equipment design. The key R&D issues identified by prior studies are:

- Lifetimes of proposed materials and components in the radiation, thermal, and chemical environments anticipated. This issue applies particularly to the transmuters, where very high neutron fluxes, liquid metals, and high temperatures potentially exist. This issue will have a significant influence on design decisions relative to system life, need for equipment maintenance/replacement, and life-cycle costs.
- Reliability and availability of ATW systems. ATW systems may be expected to operate with high availability for 60 years. All ATW subsystems would consist of newly designed equipment operating at higher temperature and/or higher energies than current, similar equipment. The design and testing of new equipment and components will be necessary to ascertain lifetime reliability and availability of systems to meet requirements.
- Adequacy of separation of uranium, TRU, and long-lived fission product elements from spent fuel and ATW transmuter fuel. This issue applies primarily to the separations and waste form components of the ATW system. The feasibility and full benefits of an ATW system will be a function of completeness of chemical separation of actinides and fission product elements from spent fuel and ATW fuel assemblies. The ability to transmute these elements, once separated, can be estimated from neutron fluxes and cross-section information. However, significant R&D remains to establish the technical feasibility of achieving high transmutation efficiencies for the long-lived fission products, particularly radioiodine.
- Quantification of total long-lived radioactivity generated in the ATW system, including spallation products, and the implications for waste streams and waste forms. This issue also applies primarily to the separations and waste form components of the ATW system. There will be radioactive wastes from an ATW system, from residual separation processes, from neutron generation processes, and from transmutation products of actinide elements. The quantities actually generated will be functions of the processes used and the separation ratios. Design features and scaling will determine how much residual waste will still require disposal in a geologic repository or other waste facility.

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2.0 Science-Based R&D Roadmap

The Administration makes no recommendation with regard to the panel's proposed research program. Should there be a national policy decision to pursue this technology, the expert group has identified a science-based research program to address the technical issues cited in the report. The pace and funding for a research program would then have to be carefully evaluated and planned in light of the currently unproven technologies involved, the potential benefits that may be gained, and current and evolving Government budget realities.

2.1 Overview

The four TWGs identified the technical issues that must be resolved before consideration to deploy an ATW system and developed corresponding R&D roadmaps for systems integration, target/blanket development, accelerator development, and separations technologies. To integrate their efforts, the TWGs worked in the framework of a specified scenario of an early deployment of an ATW system to treat 87,000 t of spent fuel. This approach facilitated the development of the total life-cycle costs of ATW but tended to select technology choices early. The principal drawbacks of this approach were that it compressed the R&D schedule to allow for early demonstration, it did not allow for an in-depth examinations of options, and it lead to large yearly costs for the early demonstration tasks.

The steering committee determined that this deployment-driven approach was successful in collecting and organizing the R&D activities to resolve identified technical issues but judged the resulting tasks and schedules to be too aggressive and more expensive than a science-driven approach. The committee further judged that a prudent, science-driven approach would implement a focused R&D program to assess the viability of ATW technologies and provide data for deciding on future development. The science-based R&D program roadmap is shown in Figure 2.1. It integrates trade studies aimed at optimizing the ATW system technical approach and configuration with focused R&D efforts aimed at preferred technology choices. The following discussions follow, explicitly and in the same order, the topics listed in the roadmap.

The six-year science-based program would focus on deriving system requirements, comparing options, developing a pre-conceptual system design, addressing the major technical issues, and providing an institutional analysis for ATW development. This science-driven program has four elements:

- **System Definition:** Concentrated in the first three years of the program, studies would first focus on deriving total system requirements. Major options for meeting these requirements would then be investigated. Technology choices for the most promising options could then be made, reference options confirmed, and key technical parameters defined. This task also would include analysis of major institutional issues relevant to development of ATW technologies. The results of these studies would help refine the R&D roadmaps. A pre-conceptual system design could be derived after five years.
- **Accelerator:** This task would analyze the causes of beam interrupts that occur frequently in current linear accelerators and would propose and test specific solutions. Critical components of the proposed linac would be developed and tested. A pre-conceptual design of the demonstration linac would be produced.
- **Fuel Treatment (Spent Fuel and ATW Fuel):** This task would investigate and test the recommended key technologies for the treatment of spent fuel and ATW fuel. For both treatment steps, a series of flowsheet studies would be undertaken to specify the processes. Small-scale experimental programs would be conducted to demonstrate the viability of these processes. Preliminary conceptual designs of the fuels processing plants would be developed. A specific task would be focused on developing and testing the waste forms produced in the processes.

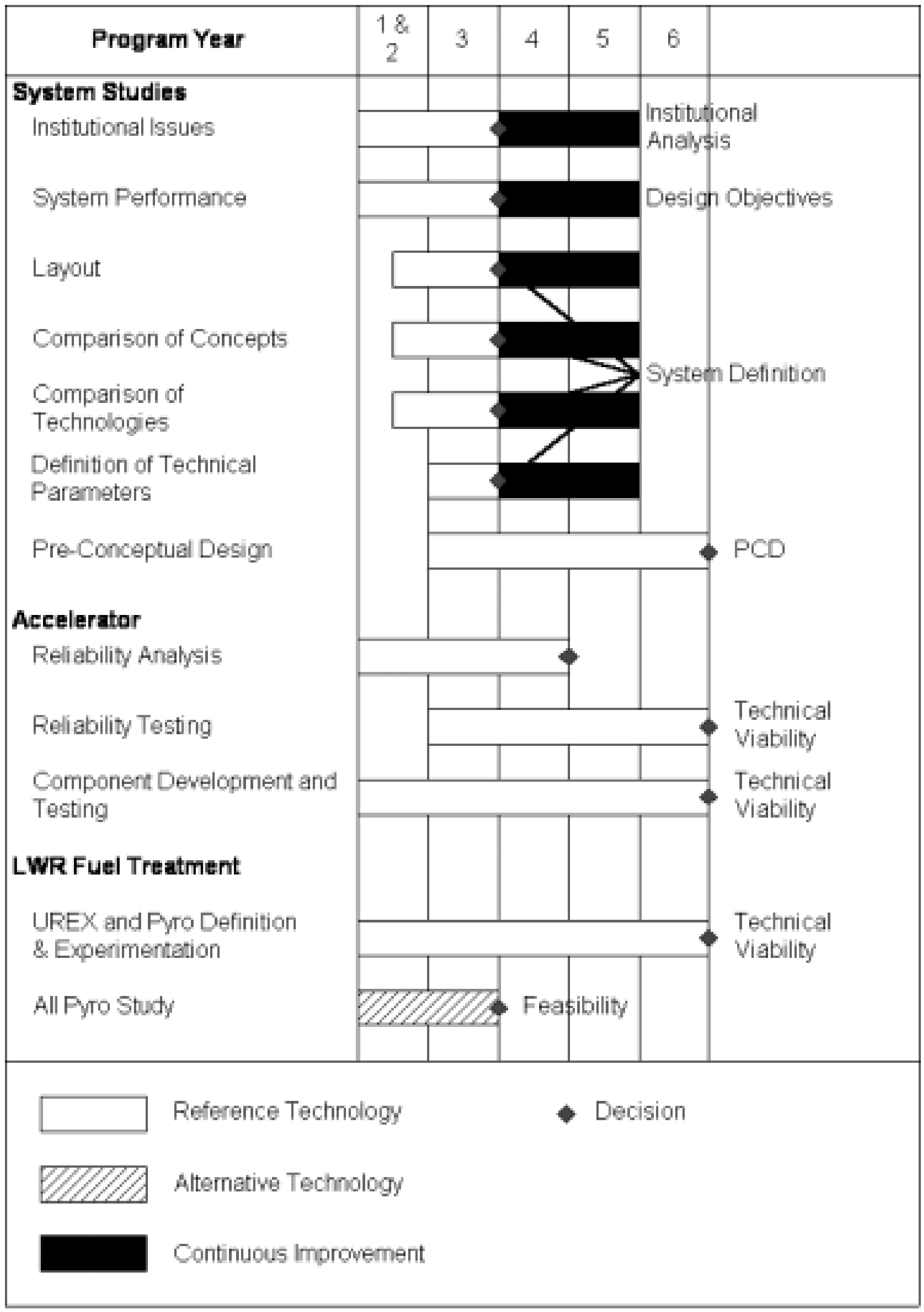

Figure 2.1. Six-Year Science-Based R&D Program Roadmap

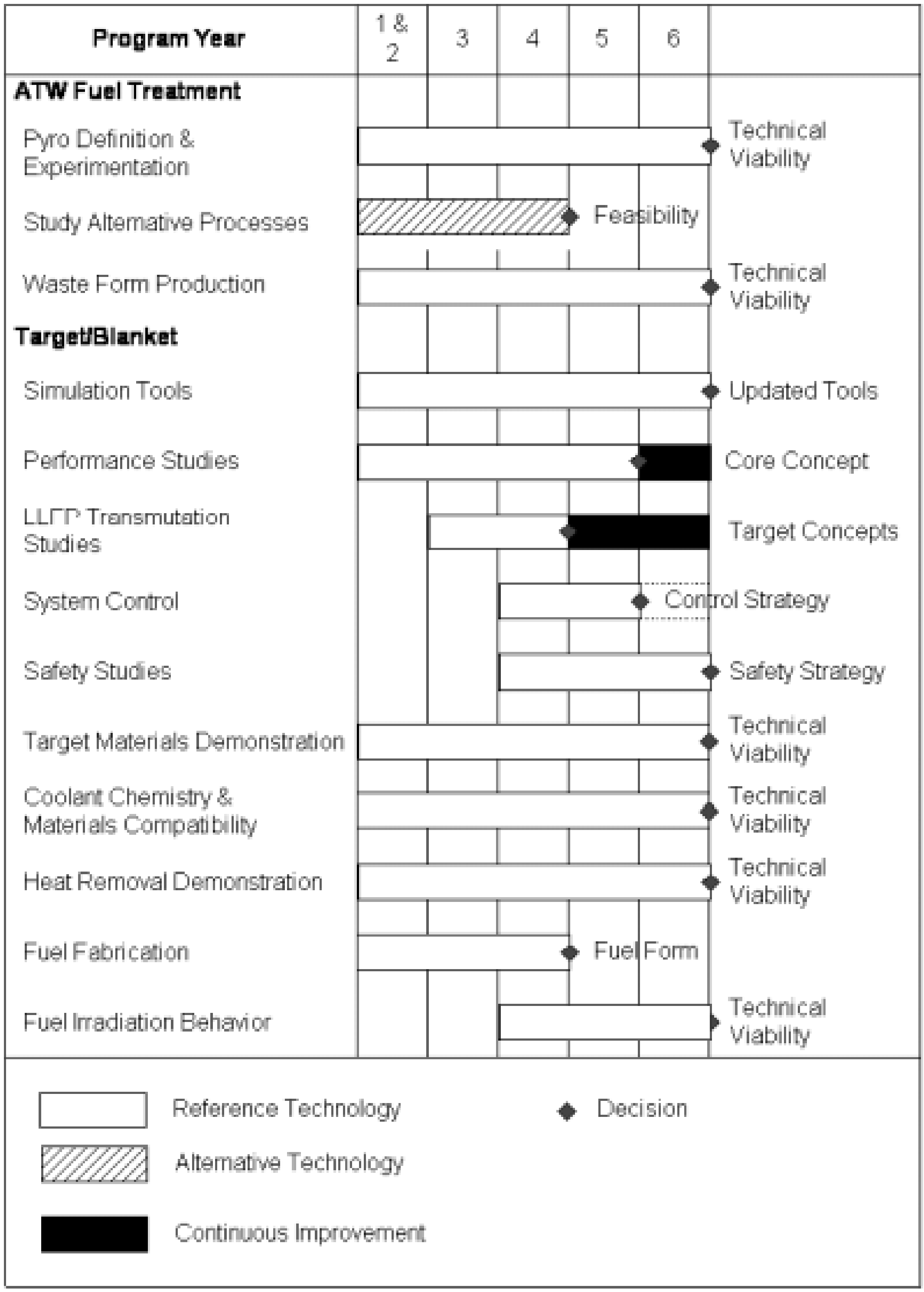

Figure 2.1. (Continued) Six-Year Science-Based R&D Program Roadmap

- **Target/Blanket:** This task would concentrate on resolving the major technical issues defined in Section 2.2. The recommended ATW fuel form would be developed and tested, LBE chemistry and heat removal issues resolved, nuclear design and safety approaches developed, and a target window material developed and demonstrated. Finally, a lead bismuth-cooled loop would be designed and constructed for installation in the Fast Flux Test Facility (FFTF), if available, to serve as a test bed for fuels and materials in realistic neutronic and thermal conditions.

The deliverables of the six-year, science-based R&D would be: 1) after three years, the systems studies would be summarized in a report, the major technical choices would be justified, and the program would issue an institutional analysis of the ATW system; 2) after five years, the effort would issue a pre-conceptual system design and a detailed RD&D roadmap to begin after year six, aiming at a complete and integrated demonstration of the ATW technologies; 3) after each year, a summary of findings and recommended future direction would be issued for each technical R&D task; and 4) a technical viability-assessment report would be issued at the end of the six-year R&D effort.

The total cost of the six-year R&D effort would be $281M. Annual and total costs by major system element are summarized in Table 2.1. Year 1 is the first year of the R&D effort. Further cost details are provided in Section 7 and in the Appendix.

The impact of this six-year effort on the deployment-driven ATW schedules and costs as developed in the TWG reports has not been estimated. The science-based roadmap provides an opportunity to eliminate certain technology options discussed in the TWG reports and thus might reduce later R&D costs, if the program were continued. Beginning in FY 2000, the responsibility for the direction of the science-based ATW research program is in the Office of Nuclear Energy, Science and Technology.

2.2 System Studies

A major task of the ATW R&D program at its inception would be to carry out a series of trade studies before launching design activities. A "top-down" approach would be used to investigate the ATW technical options, choose the most promising options, set performance objectives, and provide quantified goals for the R&D. The studies would successively concentrate on:

Table 2.1. Aggregated Annual Cost of the Six-Year R&D Plan (Millions of 1999 Dollars)

Program Year	**1 & 2**	**3**	**4**	**5**	**6**	**Total**
System Studies	4.5	6.5	3.0	2.0	2.0	18.0
Accelerator Development	6.5	12.0	16.0	13.5	10.0	58.0
Separations and Waste Forms	5.4	8.2	12.6	15.3	14.0	55.5
Target and Blanket	10.8	12.8	36.4	37.0	26.5	123.5
Program Management	3.0	4.0	6.0	7.0	6.0	26.0
Total	**30.2**	**43.5**	**74.0**	**74.8**	**58.5**	**281.0**

- Analyzing institutional issues related to ATW development.
- Defining system performance objectives.
- Defining system size and layout.
- Comparing system concepts.
- Comparing system technologies.
- Defining technical parameters.
- Developing a pre-conceptual design.

2.2.1 Institutional Analysis

Institutional challenges for the development of an ATW system fall into three broad categories: institutional capabilities, public acceptance, and regulatory/National Environmental Policy Act (NEPA) issues. Institutional capabilities relate to whether the federal government will provide the organizational and financial resources required to carry out a complex technical program extending over many decades. Public acceptance issues arise with respect to both the overall policy commitment to implement ATW and to the siting and operation of required facilities. Regulatory/NEPA issues arise with respect to the regulatory requirements for ATW activities, and NEPA requirements for development and implementation of an ATW system.

Studies of the institutional aspects should be considered as important as the technical challenges. In keeping with this, the technical development of the ATW system should be accompanied by an institutional analysis to develop recommended approaches for dealing with institutional issues.

2.2.2 System Performance Objectives

In the process of partitioning and transmuting spent fuel, the ATW system would produce radioactive waste forms that must be disposed of and thermal energy that could be converted into electricity. The goal of this task would be to set performance objectives for these functions.

Separated uranium would be a product obtained from partitioning the spent fuel. The preliminary criterion imposed on this product is that it be disposable as non-TRU class C waste, if desired. This implies a very complete separation of uranium from the TRU and fission products, which can readily be accomplished with existing aqueous processes. Alternative processes might achieve this degree of separation, but the development costs are likely to be high. Trade studies would be required to evaluate the advantages and disadvantages of producing a lower purity waste form. Alternately, the uranium could be used as fertile material in possible future breeder reactors.

HLW forms would be produced by the pyrochemical separation of TRU and fission products and from the extraction of technetium and iodine from the fission product stream. Because TRU is important to non-proliferation objectives and to repository performance, a very high removal efficiency will be required. Trade studies would optimize removal efficiency, taking into account advantages to the repository and the increased R&D and operational costs of a more complex process that might be necessary to meet recovery objectives.

Two material streams pass through the ATW system used in this analysis—a metallic TRU fuel form and fission product transmutation assemblies. The fuel form composition (TRU and zirconium content) has not yet been finalized and requires a specific trade study to define it. A higher TRU content would reduce the complexity of chemical processing but might degrade the irradiation and neutronics performance. A lower cycle transmutation would reduce the transmutation swing and associated control requirement but would require more fuel recycling steps and thus increase losses to the waste stream. The fission product irradiation assemblies require considerable development; preliminary trade studies are needed to decide whether once-through assemblies are feasible or recycling steps would be required. Several fission product assembly concepts have appeared in the literature and need to be compared and studied.

Electric power production, while not the primary objective of the ATW system, would be used to offset deployment and operations costs. The revenue generated from power sales could strongly depend on the system's thermodynamic efficiency, system reliability, and load factor. Thermodynamic efficiency can be raised by increasing the system operating temperature. Conversely, this would decrease the mechanical resistance of structural materials and, particularly in the case of LBE coolant, might significantly affect the corrosion control procedure. Trade studies would be performed to decide the optimal reactor operating conditions, considering available data from U.S. and foreign programs and balancing the potential loss of revenue with the increased risks and R&D costs required to achieve higher temperatures.

Overall system performance (waste transmutation and power production) depends directly on the system load factor. The sale price of electricity depends strongly on the reliability of the system. Thus, there is a strong incentive to increase system reliability. The reliability of standard nuclear systems has been well mastered and could be brought to a high level. The reliability of existing accelerators must be improved substantially for ATW because relatively short accelerator shutdowns may entail lengthy reactor restart operations. While an aggressive accelerator R&D program is planned, preliminary trade studies are necessary to evaluate system reliability requirements, taking into account individual system performance, interrelations between individual systems, and R&D costs and risks to achieve increased reliability. These trade studies would be used to set the R&D objectives for continuing activities.

2.2.3 System Size and Layout

The reference plant architecture devised for the deployment-driven ATW roadmap comprises two 45-MW proton linear accelerators feeding eight 840-MWt transmuters and one chemical processing plant servicing the eight transmuters. This layout was derived from various past studies: for example, APT system-level-analyses that showed a single large accelerator is much less costly than several smaller accelerators producing the same total beam power, and advanced liquid metal reactor (ALMR) studies that favor modular, moderate-size, plant-fabricated, rail-transportable reactors. The co-location of large units with their fuel processing plants was dictated by the desire to decrease the need for transporting highly radioactive fissile materials. Trade studies are needed to optimize these sizes and layout and should take into account the technical risks and costs associated with individual component size, the optimum combination of individual components, and the effect of plant sizing on the electricity supply grid.

The reference deployment rate aimed at transmuting all U.S. spent fuel in a relatively short time (90 years). The relevance of this objective must be assessed. In particular, tradeoffs between the system costs, associated risks, and expected benefits must be reviewed.

2.2.4 Comparison of System Concepts

A broad spectrum of concepts similar to ATW have been proposed in recent years. Although all aim at transmuting TRU from spent fuel, they can be classified according to fundamental properties such as neutron energy spectrum (fast and thermal), fuel type (solid, liquid), and coolant (LBE, lead, sodium, and gas). While most international programs seem to be evolving toward fast-spectrum, liquid metal-cooled subcritical assemblies driven by large linear accelerators, other attractive concepts are being investigated internationally. The United

States should investigate the merits and drawbacks of several concepts before launching into an extensive RD&D program. These studies would be performed during the first three years.

2.2.5 Choice of System Technologies

Within the framework of the reference technical concept chosen in the previous studies, several technical options that remain undecided might have significant effects on the proposed R&D program. To achieve optimal transmutation rates and energy production, each transmuter unit should operate constantly at nominal power, which can be achieved by either controlling the transmuter multiplication factor (k_{eff}) or by controlling the accelerator power (or both). The reactivity loss due to transmutation through a typical cycle is quite high and might require the use of several controlling technologies (control rods, burnable poisons). It is also directly related to the maximum fuel burnup and to the fuel cycle length and has direct consequences on the safety of the system. Several approaches can also be considered for using the accelerator beam as a control mechanism. For example, it may be practical to adjust beam power to individual transmuters using multiple low-energy linacs to inject separate beams into the main accelerator and/or use variable beam splitting arrangements. These technologies, while requiring specific R&D efforts, might offer some advantages for controlling a global ATW system. Specific studies should be planned to devise an optimized system control strategy.

The safety strategy and licensing requirements must be established for the ATW system to allow licensing of demonstration facilities. A number of preliminary safety studies would be required to establish a safety basis and modify the plant concept to mitigate potential off-normal events and their consequences. While a significant safety basis is already established through the ALMR program, the safety behavior of the ATW system would be significantly modified by using an accelerator driver (and potentially from the use of LBE coolant). The APT safety studies provide an additional framework, particularly regarding the accelerator drive and fast beam-switching systems.

A major technological choice of the ATW program would be between LBE-cooled, LBE-target designs and sodium-cooled, solid-target designs. Both approaches have advantages and drawbacks that have been widely discussed. Trade studies would be insufficient to make a final choice; therefore, an extensive R&D program and some form of international consensus would be desirable. Nevertheless, initial trade studies should be performed to define clearly the comparative technical, safety, and cost implications of both of these options and thus establish objectives for an LBE R&D program.

Another major technological choice for ATW would be between aqueous and non-aqueous spent fuel treatment options. Again, trade studies would be useful to assess the merits, risks, and costs of each option.

2.2.6 Definition of Technical Parameters

Several technical parameters must be set in order to develop R&D roadmaps that would permit the chosen technologies to meet the system performance objectives. They are classified here by basic technical fields, although strong links exist between these fields.

2.2.6.1 Spent Fuel Treatment and Pyrochemistry

The purity levels of the waste stream have already been identified as major performance parameters. Studies would be needed to investigate the trade-off between waste volume and waste form properties, associated R&D costs, and disposal costs. These studies might have a major impact on the R&D programs for the various waste forms. Various disposal and disposition options for these waste forms should be analyzed and compared.

2.2.6.2 Fuel Development

The fuel transmutation fraction objective and nominal composition must be defined very early in the R&D program. Studies involving neutronics, fuel behavior, safety, and pyrochemical treatment are needed to better understand the trade-offs between high and low transmutation fractions and high and low TRU fuel content. These two parameters would have major consequences on the system performance, and their objective values will significantly affect the definition of several R&D programs.

2.2.6.3 Blanket Development

Preliminary trade studies would be needed to define both basic and design aspects of the blanket development program. The basic aspects would concentrate on collecting the data (nuclear data, fluid and material properties) and the analysis codes (neutronics, mechanical, thermohydraulics) needed for supporting the design and safety studies. It is expected that certain novel aspects of the ATW blankets (e.g., fuel form, LBE coolant, and spallation source) would require enhancing the existing data and codes. Preliminary studies would concentrate on understanding potential sources of uncertainties, quantifying them, and defining R&D objectives to reduce them. Design-level trade studies are also required to understand and quantify the impact of several parameters on the total system characteristics. The major parameters are the following:

- Blanket multiplication factor, which reduces the accelerator power requirements when raised but might also decrease the safety margins and operational flexibility of the system.
- Fuel composition, transmutation rate, and management strategies.
- Blanket control strategy.
- Degree to which natural convection participates in the pumping requirements, which must be investigated, taking into account specific design approaches and safety consequences.
- Operating temperature of the blanket.
- Neutronic feasibility of various designs for fission product transmutation assemblies, which must be investigated, taking into account achievable transmutation rates, recycling and treatment performances, and safety consequences.

2.2.6.4 Spallation Target Development

Early design studies would be run in conjunction with blanket design studies to understand the trade-offs between beam delivery characteristics (size of footprint, location of window, width of buffer) and blanket characteristics (damage to fuel, power peaking, burning rate distribution, and transient behavior).

2.2.6.5 Accelerator Development

The pre-conceptual design and trade studies that should be carried out include:

- Integration of the accelerator design into the control strategy.
- Development and analysis of reference accelerator designs, including cryomodule architecture, radio frequency (rf) system architecture, cryosystem concept, beam-sharing and control, and beam-transport architectures for ATW plants.
- Assessment of basic accelerator parameters such as cavity frequency, cavity gradient, cryogen temperature, rf generator size, rf coupler power, focusing lattice-period and type, power supply size and configuration, etc.
- Beam dynamics analysis and simulations to assess optical matching requirements, beam halo minimization, and sensitivity to machine imperfections.

- Mechanisms for ensuring redundancy, reducing vulnerability to component failures, and rapid recovery from faults.
- Fabrication and manufacturing strategies to reduce costs and improve component performance.

2.2.7 Deliverables

After three years, the systems studies would be summarized in a report, which would address the major technical choices and institutional issues of the ATW system. After five years, the R&D program would issue a pre-conceptual system design and a detailed RD&D roadmap that would begin after year six, aiming at a complete demonstration of the ATW technologies.

2.2.8 Estimated Costs

Estimated costs of the systems work are shown in Table 2.2.

2.3 Accelerator R&D Roadmap

During the first six years of an ATW R&D program, accelerator work would be focused on:

- Addressing the beam reliability issue through system analysis and component testing
- Developing and testing key components expected to have a high impact on the plant and demonstration machine designs and that address performance requirements
- Determining a pre-conceptual design for a demonstration accelerator.

Early in the six-year R&D program, trade studies would examine the question of overall ATW system architecture, especially the issue of whether multiple transmuters should be driven by a single high-power accelerator or each transmuter should be supplied by its own (lower power) accelerator. Factors such as capital and operating costs would be balanced against reliability, availability, and operability, and the outcome of such a study may impact the R&D program.

2.3.1 Beam Reliability Analysis

Assessing reliability performance and developing and testing ultra-reliable equipment would be a multifaceted R&D program aimed to achieve a frequency of beam interrupts three or more orders of magnitude lower than that which exists in most operating accelerators. The program would initially identify the causes of unreliability or failure in the equipment systems that affect beam acceleration and delivery to the transmuters. In the next step, these equipment systems will be redesigned and rebuilt to eliminate to the extent possible

Table 2.2. Cost of the Systems Work for the Six-Year, Science-Based R&D Program (Millions of 1999 Dollars)

Program Element	Year 1 & 2	Year 3	Year 4	Year 5	Year 6	Total
System definition	4.5	4.5	0.0	0.0	0.0	9.0
System pre-conceptual design	0.0	2.0	3.0	1.0	2.0	8.0
Demonstration plan	0.0	0.0	0.0	1.0	0.0	1.0
Totals	**4.5**	**6.5**	**3.0**	**2.0**	**2.0**	**18.0**

the causes of failure and tested to verify the improved performance. The linac design would also be assessed for modifications that could be introduced to the standard architectures to make the accelerator system as a whole less sensitive to failures of individual subsystem elements.

Reliability and continuity of the ATW accelerator beam is a demanding new requirement significantly different than the present operating requirements for large research accelerators and the APT accelerator. These accelerators require that time-integrated beam availability be high and the accelerator and beam-transport components be protected from damage due to off-normal beam conditions. Eliminating beam interrupts, which occur with relatively high frequency (from several per day to one per hour) has not been a driving issue. For ATW, power transients to the transmuter fuel assemblies must be minimized to avoid damage from thermal cycling and shock waves, and large power transients to the electric power grid must be reduced to a low number per year.

The issue of beam reliability would be addressed both through analysis and hardware development and testing. The first path will involve assessing equipment and subsystem failures and their causes, their prevention and recovery, and system design to provide redundancies that would ameliorate the impacts of failures. Reliability analysis would begin in the first year of the program and continue for up to four years.

2.3.2 Beam Reliability Testing

A combination of existing equipment systems (low-energy demonstration accelerator [LEDA], prototype APT medium-beta cryomodule test stand) and newly designed reliability demonstration test stands will be used to carry out the reliability test program. Reliability development and testing would start in the second year and proceed for four years. This R&D effort program would involve testing and improvement of existing operating systems, such as the LEDA front-end accelerator prototype built for APT, and building and testing key component systems designed specifically to operate with few failures. The results of this testing would be used for design of a demonstration ATW accelerator. If built, reliability testing would continue throughout the operation of a demonstration accelerator to establish final goals and designs for ATW plants.

2.3.3 Component Development and Testing

The current reference deployment-driven ATW plant architecture calls for 45-mA continuous wave 1-GeV proton linacs, with the beam distributed equally to four separate transmuters using rf splitters, as shown in Figure 2.2. Each plant would incorporate two of these accelerator/beam-transport systems. The beam energy is chosen at 1 GeV to obtain efficient conversion of beam power to spallation-neutron production, and the beam power is chosen to drive the transmuters at their design value of k_{eff}.

2.3.3.1 High-Gradient Superconducting rf Cavities

For the superconducting rf cavity R&D program, the most important technical issues involve demonstrating reliable and reproducible attainment of high accelerating gradients in the high-beta linac multicell cavities simultaneously with a high cavity-quality factor. The latter is needed to minimize the heat load to the plant cryogenic system. It is also important to demonstrate that suitable levels of rf power can be coupled into the superconducting cavities under these conditions.

Most of the accelerator would be constructed from niobium superconducting rf cavities operated at temperatures near 2°K. This maximizes the efficiency by which rf power is converted to beam power, essentially eliminating rf losses in the cavity walls and reducing the number of rf power systems required to drive the beam. Because very high accelerating gradients can be achieved in superconducting rf cavities, the linac length is minimized. The combined effects of reducing length and rf power minimize accelerator capital costs. Eliminating rf wall losses minimizes the power that must be recycled to the plant to operate the accelerator, and thus reduces operating costs.

The reference ATW linac design calls for superconducting cavities with 10-MV/m gradients in the high-velocity region of the accelerator. In addition, new types of superconducting accelerating structures (spoke resonators) are being developed for the low velocity region ($\beta < 0.5$), which provide the potential in an ATW linac for extending the superconducting cavities down to much lower energy than in the APT linac. The additional gains in power efficiency and shorter length are significant but not as important as the gains made by going to higher gradient in the high-beta superconducting linac. The main improvement over the APT linac design is larger beam apertures, which would reduce beam losses and improve operability in the low-beta part of the linac.

2.3.3.2 High-Efficiency rf Generators

For developing advanced rf generators, the main issue is demonstrating high-efficiency conversion of dc power to rf power in a simple, reliable, and low-cost device. This hardware development activity has the greatest potential impact, after high-gradient superconducting cavities, on lowering accelerator capital and operating costs. The best opportunity for improving the power efficiency of an ATW linac is in the dc-rf conversion efficiency of the rf generators that supply microwave power to the accelerating cavities. The reference design of the rf power system is based on the use of high-power (MW-class) klystrons, as in APT. Inductive-output tubes (IOT) (sometimes called klystrodes) have considerably higher efficiency and are more compact. The APT program is developing a high-power IOT prototype, but other designs with intrinsically higher reliability may be preferable for powering an ATW accelerator.

2.3.3.3 rf Beam Splitters

For developing an rf beam splitter, the performance issue involves the level of deflection field that can be achieved reliably in the superconducting cavities and whether the desired deflection angles can be achieved without beam loss. The first issue can be addressed by testing the splitter cavities with rf power alone; the second requires a beam test, which could be carried out either on LEDA or on the Los Alamos Neutron

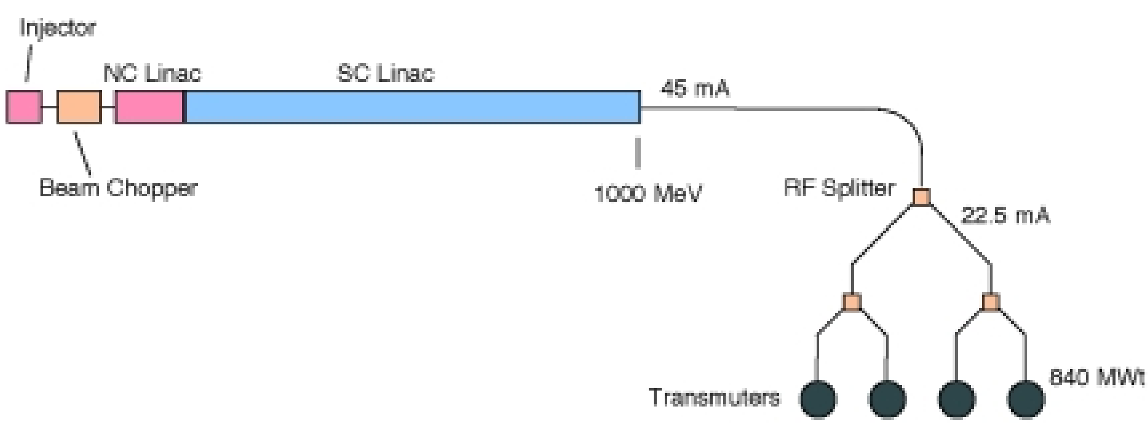

Figure 2.2. Reference Accelerator and Beam-Transport Concept for the Deployment-Driven ATW plant

Science Center (LANSCE) linac. The ATW plant reference concept calls for subdividing the continuous wave beam from each high-power linac into four equal-intensity continuous wave beams, using rf beam splitters. These beam splitters would be constructed of sequences of superconducting rf cavities supplying deflection (transverse) fields instead of accelerating fields. Similar devices have been built and tested for particle separation in high-energy beams, and the ATW beam splitting requirements appear practical. However, the beam splitter is the major component that must be demonstrated to confirm the feasibility of producing multiple CW beams for driving several transmuters with a single accelerator.

2.3.4 Pre-Conceptual Accelerator Design

A complete pre-conceptual design would be developed for the accelerator and beam transport system that could be built for an ATW demonstration facility. The type, beam power, and staging of this accelerator would result from trade studies and system analyses to be performed during the first three years of the R&D program. In this part of the six-year effort, the pre-conceptual design of the accelerator and beam transport would define the main features of the accelerator performance and architecture, provide a basis for a conceptual design, outline additional R&D programs needed to reduce risks in the design, and provide a preliminary cost estimate.

2.3.5 Deliverables

The deliverables for the six-year accelerator R&D program and pre-conceptual design would be as follows.

Superconducting rf cavity development:

- Multicell cavities operating at gradients of greater than 10 MV/m with high Q (quality factor) values.
- Power couplers operating at level required in pre-conceptual linac design.

High-efficiency rf generator:

- Prototype rf generator operating with high dc to rf conversion efficiency and high reliability, at power levels required in pre-conceptual linac design.

rf beam splitter:

- Prototype multicell cavity superconducting rf beam splitter operating at the field required for adequate beam deflection.

Reliability analysis:

- Report describing results and conclusions of reliability analysis, with implications and guidance for architecture and equipment design in ATW linacs.

Reliability testing:

- Demonstrations of key accelerator equipment that operates with ultra-low failure rates.
- Studies of key equipment systems describing failure mechanisms, and progress in modifying these systems to improve reliability.
- Guidelines for design and construction of the next generation of key equipment systems for negligible failure rates.

Pre-conceptual design:

- Report describing pre-conceptual design of accelerator and beam transport system for a demonstration system.
- Preliminary cost estimates and schedule for implementation of a demonstration linac.

2.3.6 Integrated Costs

The costs of accelerator R&D and pre-conceptual design are shown in Table 2.3.

2.3.7 Major Deferred R&D Needs for the Accelerator

The six-year R&D program would advance the knowledge of the accelerator system. However, some major R&D issues would have to be scheduled later in succeeding years, should the program be continued. Some of these R&D needs are: 1) confirmation of design parameters and conduct of risk reduction studies; 2) integration of high-beta superconducting cavities and new superconducting quadrupoles into cryomodule prototypes; 3) development of lower-beta superconducting cavities and cryomodules; 4) prototyping of rf system components, such as windows, circulators, and vacuum valves; 5) integration of rf splitter cavities into a cryomodule that would be tested with beam; and 6) integration of components into an ATW demonstration accelerator, which would serve as a test bed for improvements in overall accelerator system reliability.

2.4 Fuel Treatment and Waste Forms R&D Roadmap

This roadmap concentrates on those aspects of an ATW chemical separations system that appear to offer the greatest potential for meeting overall systems performance. Separations technologies are well developed, which facilitates evaluating their relative merits in the specialized application to ATW system requirements.

The six-year R&D program would be conducted largely by analysis, supplemented by highly focused, small-scale laboratory experimentation. The greatest need at the end of the six-year R&D period is for pilot-scale process studies. Many chemical processes behave differently at larger scale than they do in laboratory bench-scale experiments. It is expected that the needed pilot-scale studies could be done in existing glovebox and hot cell facilities throughout the DOE complex.

Table 2.3. Cost of the Accelerator R&D and Pre-Conceptual Design for the Six-Year R&D Program (Millions of 1999 Dollars)

Program Element	Year 1 & 2	Year 3	Year 4	Year 5	Year 6	Total
Reliability Analysis	1.5	1.5	1.0	0.0	0.0	4.0
Reliability Testing	0.0	3.0	5.0	7.0	5.0	20.0
Superconducting rf Cavities	3.0	4.0	5.0	3.0	2.0	17.0
High-Efficiency rf Tube	1.0	1.5	1.5	0.5	0.5	5.0
rf Beam Splitter	1.0	2.0	1.5	1.0	0.5	6.0
Pre-conceptual Design	0.0	0.0	2.0	2.0	2.0	6.0
Totals	**6.5**	**12.0**	**16.0**	**13.5**	**10.0**	**58.0**

2.4.1 Spent Fuel Treatment

The baseline process selected for initial focus combines aqueous solvent extraction and pyrochemical processes to accomplish efficient separation of uranium, technetium, iodine, and TRU from the spent fuel in the head-end step. An aqueous solvent extraction process was selected to treat spent fuel because of the commercially proven ability of such methods to handle very large volumes.

2.4.1.1 UREX and Pyro Definition and Experimentation

The solvent extraction process proposed is a variation of the widely used PUREX process, modified for uranium separation only and called "UREX." Plutonium and other TRU would be left in the aqueous raffinate together with the non-gaseous fission products. This stream would then be sent to a pyrochemical process where the product is precipitated, filtered, and calcined to place the constituents in the form of oxides, reduced to the metallic state, and then electrorefined to separate the TRU and selected long-lived fission products for transmutation in the ATW transmuter.

Many of the key technical issues associated with the UREX process can be addressed without extensive experimentation. Hence, the proposed work scope includes comprehensive process modeling studies to obtain the most efficient design of the overall UREX process and optimize reagent requirements. It is not standard commercial practice to recover iodine; therefore, some development and optimization of iodine recovery methods will be required. An important consideration is recovering iodine in a form that will be readily usable in transmutation assembly fabrication. Other issues include the selection of a plutonium reductant that will not add waste volume, effective separation of technetium and neptunium from uranium, and validation of the oxalate precipitation process. The potential need for an additional hull-leaching step to meet the actinide recovery goal is also a technical concern.

A comprehensive modeling effort would be carried out to more fully define the several aspects of the UREX solvent extraction process. This effort would be supported by experimental studies to establish certain solution chemistry properties of technetium and neptunium not currently available, which would facilitate efficient extraction of these elements. Other experimental work on the UREX process would be aimed at selecting the optimum plutonium reductant and validating an oxalate precipitation process essential to subsequent recovery of the TRU for transmutation. Cladding hull leaching studies would be performed with actual commercial spent fuel rods to assess the need to include such a process step, and if so, to establish optimum methods for recovering residual actinides and fission products. The pyrochemical process for TRU separation would be modeled thoroughly to determine scale-up issues that might require further experimental development. Efforts would also be directed toward optimizing electrode configurations and materials for recovering lithium used to reduce actinide oxides to their metals and improving the process for consolidating the TRU product recovered during electrorefining.

2.4.1.2 All-Pyro Study

The potential for using an all-pyrochemical process for treatment of spent fuel would be assessed during a two-year trade study to be carried out in the early stages of the R&D program. Should the results of this study be favorable to the pyrochemical process, the R&D program could be re-oriented. Because the pyrochemical process would be replacing the UREX aqueous front-end separation step, while the pyrochemical processes for other downstream separations steps would be unchanged, the emphasis here would be to evaluate the ability to develop a cost-effective pyrochemical process for treatment of the large tonnage quantities of commercial oxide spent fuel. Also of concern is the feasibility of meeting purity requirements for the recovered uranium product.

2.4.2 ATW Fuel Treatment

Processing of irradiated ATW fuel would be necessary to recover un-transmuted transuranics and extract newly generated fission products for recycle through the transmutation system. The method proposed for processing this fuel, assumed for roadmapping purposes to be TRU and various fission product elements contained in a zirconium metal matrix, is one of the least technically mature steps in the overall flowsheet. The selection of a pyrochemical processing method for this fuel was a logical choice because of its robust and compact nature, its ability to operate efficiently and generate small volumes of waste, and its potential to significantly reduce processing costs. In contrast to processing LWR spent fuel, high material throughput is not required to treat irradiated ATW fuel. Two options were considered for treating this fuel: a chloride volatility process (with two variants) and an electrometallurgical process. The difference between the two options is the method by which zirconium, the major component of the fuel is removed from the TRU and fission products.

The principal technical issue related to the chloride volatility process is the method that would be used to collect the volatile chloride species, separate these species from the gaseous fission products, and collect iodine for subsequent transmutation. Other issues include the efficiency of extraction of residual salts from the chlorination process and the recovery of TRU from this salt, a process that has not been demonstrated at a practical scale.

Emphasis during the six-year R&D period would be placed on process design, flowsheet analysis, and modeling to derive a more complete definition of the pyrochemical process and identify areas of needed R&D. Using the chloride volatility process depends largely on the selection of the ATW fuel assembly composition. Close coordination with the target/blanket development activity would be essential. In anticipation of using a zirconium matrix fuel material, key experiments related to chloride volatility should be carried out. Experiments would cover such issues as collection methods, iodine recovery, residual salt extraction, and the electrowinning of TRU from the residual salt.

A four-year trade study would compare alternative processing methods (both aqueous and pyrochemical) with the chloride volatility process. A comprehensive trade study would allow thorough evaluation of process options and position the technologists for a possible shift in processing methods should the ATW fuel composition be significantly different than that presently envisioned.

2.4.3 ATW Waste Forms

The HLW forms resulting from the fuel treatment processes are quite similar to those resulting from electrometallurgical treatment of experimental breeder reactor II (EBR-II) spent fuel, making it possible to capitalize on advances achieved in other programs and focus near-term development on issues specific to the ATW system.

R&D activities related to waste form production can be limited to issues not addressed by other programs. A primary issue is the use of a different alloy composition (zirconium-8 stainless steel) for the metal waste form. Characterization of the structure of this alloy and its properties, especially leach resistance, will be necessary to ensure that this alloy composition can accept the contemplated radionuclide content without deleterious effects on physical and chemical properties of concern to repository performance. Also to be resolved is how the metallic fission product constituents of this waste form can be separated from the electrolyte salt and melted together with the cladding hulls without generating excessive secondary wastes from unusable melting crucibles. Means to minimize the volume of HLW produced, particularly in the case of the ceramic waste form, must also be emphasized. System preconceptual design can be important in limiting these waste volumes and reducing the quantity of secondary wastes produced in the overall process.

2.4.4 Fuel Treatment Deliverables

The six-year R&D period is expected to establish, at a high level of confidence, the reference processes for ATW separations and waste form production operations. Comprehensive process design and analysis studies would quantify the performance capabilities of the overall process and support decisions regarding further development and implementation of the ATW system. System pre-conceptual design studies would position the program for moving ahead with critical pilot-scale tests and preparing process demonstration roadmaps.

2.4.5 Estimated Costs

Estimated costs for the six-year R&D period are shown in Table 2.4.

2.4.6 Major Deferred R&D Needs for Fuel Treatment and Waste Forms

The six-year R&D program would be conducted largely by analysis, supplemented by highly focused, small-scale laboratory experimentation. Some major R&D issues have been deferred to succeeding years, should the program be continued. Deferred issues include: 1) means for conversion of technetium and iodine to forms usable for transmutation targets, 2) the recovery and recycle of zirconium from LWR cladding and ATW fuel, 3) optimization of anode/cathode design for the transuranic electrowinning process, 4) possible use of the TRUEX process for technetium recovery during LWR fuel processing, and 5) development of vessel and piping materials for use in the chloride volatility process.

2.5 Target/Blanket R&D Roadmap

Resources available in a science-based R&D program would be directed toward resolving technical issues that exert the greatest impact on the success of proposed target and blanket technologies. Many of the issues to be addressed in the initial six-year R&D program would determine the feasibility of the proposed ATW concepts.

A three-year period of trade studies, where several options and technologies would be assessed, is expected at the start of the program, with initial down-selections at the end of the third year. A complete system pre-conceptual design is expected after five years. The adoption of proven blanket and thermal-hydraulics technologies and the use of solid fuels, which are readily testable extensions of known technology, would provide an initial basis for the required research and development for the ATW target and blanket system.

2.5.1 Target/Blanket R&D Activities

The roadmap in Figure 2.1 identifies ten R&D areas for the target/blanket portion of an ATW system.

2.5.1.1 Simulation Tools

Computer-based simulation and calculation tools would be upgraded and/or developed, as necessary, to support the design and performance of trade and system studies. Additional computer tools would be needed for development of conceptual designs. This development and testing of computer-based tools would continue throughout the R&D studies.

Table 2.4. Cost of the Six-Year Science-Based R&D Program for Developing ATW Separations and Waste Form Technologies (Millions of 1999 Dollars)

	Year 1 & 2	Year 3	Year 4	Year 5	Year 6	Total
Spent Fuel Treatment	0.0	0.0	0.0	0.0	0.0	0.0
UREX Process	1.4	1.6	3.1	2.0	1.5	9.6
Pyro-A Process	0.5	0.6	1.3	1.8	1.2	5.4
All-Pyro Option	0.2	0.3	0.0	0.0	0.0	0.5
System Pre-Conceptual Design	0.0	0.0	0.6	0.9	0.7	2.2
ATW Fuel Treatment	0.0	0.0	0.0	0.0	0.0	0.0
Pyrochemical Process	2.2	3.9	4.8	6.7	6.4	24.0
Alternative Processes	0.3	0.6	0.5	0.0	0.0	1.4
System Pre-Conceptual Design	0.0	0.0	0.5	0.8	1.0	2.3
Waste Form Production	0.0	0.0	0.0	0.0	0.0	0.0
Metal Waste Form	0.3	0.5	0.8	1.2	1.2	4.0
Ceramic Waste Form	0.5	0.7	1.0	1.5	1.5	5.2
System Pre-Conceptual Design	0.0	0.0	0.0	0.4	0.5	0.9
Total	**5.4**	**8.2**	**12.6**	**15.3**	**14.0**	**55.5**

2.5.1.2 Performance Studies

Calculations to determine blanket performance are required for continued development of ATW concepts. Blanket design configurations would be evaluated, and evolution of isotopic composition and system performance characteristics with recycle would be characterized. Approaches for efficient transmutation of long-lived fission products would be investigated. Dynamic response of the coupled target and blanket would also be investigated, with results applied to the formulation of monitoring, control, and safety requirements. The nuclear safety of target and blanket concepts would be analyzed early in the program to identify issues to be resolved through design. The adequacy of existing data, methods, and codes for ATW nuclear design and safety assessments would be evaluated, and high-priority adaptations of existing computational tools would be implemented.

2.5.1.3 Long-Lived Fission Product Transmutation Studies

One of the key issues for the ATW system studies would be assessing the feasibility of processing, collecting, and immobilizing technetium and iodine from spent fuel and ATW fuel. A follow-on study would evaluate the ability to fabricate technetium and iodine into transmutation elements. An overriding consideration is the feasibility of transmuting significant quantities of these isotopes in an ATW system or any reasonable nuclear system.

2.5.1.4 System Controls

Research in this area would address the need to develop ATW blanket design and operating approaches that enable transmutation of transuranic actinides and long-lived fission products as economically and safely as possible. Specific issues to be resolved by the research include: 1) control of the degree of subcriticality, 2) control of burnup reactivity, 3) control of system dynamic behavior, 4) formulation of monitoring and control, and 5) establishing the validity of databases and simulation tools used for core design and safety confirmation.

2.5.1.5 Safety Studies

Research in this area would address the need to develop ATW blanket design and operating approaches that enable transmutation of transuranic actinides and long-lived fission products as economically and safely as possible. Specific issues to be resolved by the research include: 1) optimization of the degree of subcriticality, 2) minimization and accommodation of burnup reactivity loss, 3) accommodation of feed composition variation with recycle, 4) characterization of system dynamic behavior, 5) formulation of safety protection requirements, 6) identification and resolution of safety issues, and 7) establishing the validity of databases and simulation tools used for core design and safety confirmation.

2.5.1.6 Target Materials Demonstration

Key issues to be resolved with development of spallation target concepts for an ATW system include identification of materials for the target window and structures and evaluation of design concepts. Resolving these issues would answer the remaining feasibility issues associated with the LBE target and would provide a sound basis for further design.

Prospective target-window materials will be identified for further investigation. Experimental studies of material property degradation under proton irradiation (proposed to be conducted using the LANSCE facility at LANL) will be conducted to identify promising candidate materials and to begin determination of materials performance and design limits. Design concepts for LBE and tungsten targets will be advanced through analysis and small-sale laboratory testing.

2.5.1.7 Coolant Chemistry and Materials Compatibility

R&D efforts proposed include the design and operation of an LBE loop to be used for study of chemistry control techniques, materials compatibility studies, and heat transfer and flow characteristics (an effort that would be coordinated with those addressing LBE heat transfer and component design issues). Within the early R&D period, it will be important to establish and demonstrate the ability to control LBE chemistry (e.g., oxygen content) as required, and to identify materials that are compatible with LBE temperatures as high as 600° C. Successful demonstration will indicate good prospects for developing an LBE-cooled ATW system. There are no significant issues associated with chemistry or materials compatibility of sodium-cooled or helium-cooled ATW systems to be resolved in the initial R&D period.

Agreements for LBE technology transfer would be established with Russian laboratories. One or two LBE loops would be constructed in the United States so U.S. personnel would gain experience with LBE and LBE chemistry. A U.S.-Russia collaborative program is proposed to determine desirable LBE coolant conditions for ATW application and to test materials in high-temperature LBE. Russian alloys that were developed for compatibility with LBE will provide the basis to compare LBE compatibility of U.S. alloys that may be proposed for consideration. At the end of the six-year R&D program, promising alloys (Russian and/or U.S.) would be identified for LBE applications, and the ability to develop an LBE-cooled primary system would be established.

Fast spectrum operation will require the use of nuclear coolants that do not significantly thermalize the neutrons before they have a chance to fission the TRU. Sodium, LBE, and helium are all suitable coolants for fast spectrum operations. In varying degrees, considerable reactor experience exists for all three coolants, and they are compatible with the selection of metallic fuels. Each coolant offers distinct advantages and drawbacks; careful assessment will be required to select the optimal choice.

2.5.1.8 Heat Removal Demonstration

It appears that Russian technologists have successfully deployed heat removal and ancillary components in LBE systems. Therefore, it is important to transfer technology from Russia to determine if a U.S. program can successfully and cost-effectively develop such components for a LBE-cooled ATW system. The heat transfer properties of LBE must be measured to evaluate preliminary design concepts and safety. Laboratory-scale testing of LBE test loops is necessary to develop experience with LBE heat removal and component performance. The results of these initial investigations would allow assessment of the potential for development of an LBE-cooled ATW system.

The agreements to be established for LBE technology transfer would also provide for transfer of LBE heat transfer technology. A U.S. experimental program would measure heat transfer properties of LBE and will include the fabrication and testing of bench-scale LBE pumps and heat exchangers. The objectives for the laboratory-scale work will be to develop a U.S. base of expertise with operation of LBE and to understand the unique characteristics of LBE heat removal relative to that of sodium. Such expertise will be required to properly assess the prospects for success of an LBE-cooled ATW development program.

2.5.1.9 Fuel Fabrication

The preferred ATW fuel form proposed is based on success with similar fuel forms for other applications; however, there are no data with the particular composition(s) to be considered for the envisioned ATW concepts. It will be important to determine that the fuel can be successfully fabricated, to determine basic properties of the fuel form, and to demonstrate irradiation performance prospects through simple testing. Suitable alternative forms and the associated implementation issues should also be identified. Forms and fabrication/processing schemes for transmutation of long-lived fission products must be evaluated to support questions regarding feasibility and desirability of long-lived fission product transmutation.

Laboratory-scale efforts would begin immediately to test proposed techniques for fabricating the proposed fuel form and to measure properties of the proposed fuel alloy composition(s). As early as possible, samples would be fabricated for irradiation testing (a special irradiation experiment in the Advanced Test Reactor is proposed) for an early indication of irradiation behavior. ATW fuel development would include the demonstration of fuel assembly hardware and cladding compatibility with LBE in the appropriate neutron flux environment.

Russian success with LBE coolant required control of the oxygen content in the LBE to ensure maintenance of a protective oxide film on the surfaces of component materials. Therefore, irradiation testing of ATW fuel in fast flux and LBE coolant will be essential to developing a reliable blanket fuel and to providing a performance database to eventually support fuel licensing. The best facility worldwide to perform such tests is FFTF at Hanford, Washington. If FFTF is available for irradiation testing, then it is proposed that an LBE test loop be fabricated and utilized for fuel feasibility and integral rod tests. The prospect of implementing an LBE test loop in FFTF may attract substantial international support (France, Japan, Belgium, and Italy) because LBE is currently of great international interest in view of its possible use as nuclear coolant. Construction and operation costs of the LBE loop at the FFTF reactor could possibly be shared among the international participants and the United States.

2.5.1.10 Fuel Irradiation Behavior

Solid metallic fuels are the primary fuel choice for ATW because of their compatibility with pyrochemical fuel reclamation at the back end of the ATW cycle. An added bonus of metallic fuels is their higher thermal conductivity and greater resistance to thermal shocks (compared to ceramic fuels). Using liquid fuels would avoid burnup reactivity changes through adding fissile material on-line and removing poisons. However, compared to solid fuels, liquid fuels present much larger unknowns associated with materials, operation, and general engineering approach. Liquid fuel options would be considered in the trade study phase.

Fast spectrum operation is consistent with a choice of solid fixed ATW fuel (as opposed to liquid), because:

- TRU have a considerably better ratio of fission-to-parasitic capture for fast neutrons than for thermal neutrons.
- The effects of fission product poisoning on reactivity are less severe.
- Radial power peaking is less pronounced.

Conversely, using a thermal spectrum for fertile-free ATW systems is possible only if the fuel fissile content can be regularly replenished during operations because of a larger impact of fission product poisoning in the thermal spectrum. Such systems would implement liquid fuels, like molten salts, or "semi-fluid fuels," as in the pebble bed gas-cooled reactor concept.

2.5.2 Deliverables

The six-year R&D period would establish, at a fairly high level of confidence, the reference technologies for an ATW target and blanket. Investigations and experiments would refine parameters and values to be used for pre-conceptual and conceptual design activities and would address the feasibility of certain proposed technologies. At the conclusion of the six-year period, a pre-conceptual target and blanket design would be prepared, along with a basis for selection of reference and alternative technologies that may be pursued through subsequent development.

2.5.3 Estimated Costs

Estimated costs for the six-year R&D period are shown in Table 2.5.

Table 2.5. Cost of the Six-Year, Science-Based R&D Program to Develop ATW Target and Blanket Technologies (Millions of 1999 Dollars)

	Year 1 & 2	Year 3	Year 4	Year 5	Year 6	Total
Nuclear Design and Safety	1.6	1.6	3.0	3.2	3.4	12.8
Target Technology	1.5	1.6	11.5	11.5	1.5	27.6
Coolant Chemistry and Materials Compatibility	3.1	3.3	3.3	3.3	3.3	16.3
Heat Removal and Ancillary Systems	2.8	3.5	3.4	3.1	3.1	15.9
Fuel Technology	1.8	2.8	3.2	3.9	3.2	14.9
FFTF LBE test loop or equivalent	0.0	0.0	10.0	10.0	10.0	30.0
Pre-conceptual Design	0.0	0.0	2.0	2.0	2.0	6.0
Total	10.8	12.8	36.4	37.0	26.5	123.5

3.0 International Cooperation & Collaboration

International interest in developing separations and transmutation technologies for waste management has been increasing over the last several years. Japan has made a large financial commitment for R&D to partition TRU from HLW and transmute TRU in either reactors or accelerator-driven transmuters. Coordinated European programs have considered TRU burning in fast reactors and in accelerator-driven transmuters. Both Japanese and European programs are examining non-aqueous separations techniques and enhanced aqueous processing. The technologies among these programs are converging, creating the potential for international collaborations. The undertaking of ATW R&D in the United States offers the opportunity for collaboration with other international programs, which could reduce duplication of efforts and maximize the benefits of research in topics of common interest. Such collaboration might take the form of shared sponsorship of facilities and experimental programs or comparative studies.

3.1 Summary of Current ATW Programs Worldwide

3.1.1 International Fuel Cycle Applications of ATW

Options that foreign countries are pursuing in the area of nuclear waste transmutation fall into three generic areas: mixed-oxide (MOX) fuels in LWRs, waste transmutation (including plutonium and minor actinides) in fast critical reactors, and waste transmutation in accelerator-driven subcritical assemblies. In the United States, ATW is being considered in the context of spent fuel resulting from a once-through fuel cycle. Other nations are pursuing ATW as an integral component of their fuel management schemes. The differing approaches adopted by these organizations, illustrated in Figure 3.1, demonstrate the flexibility that ATW might offer as a component of future nuclear energy scenarios.

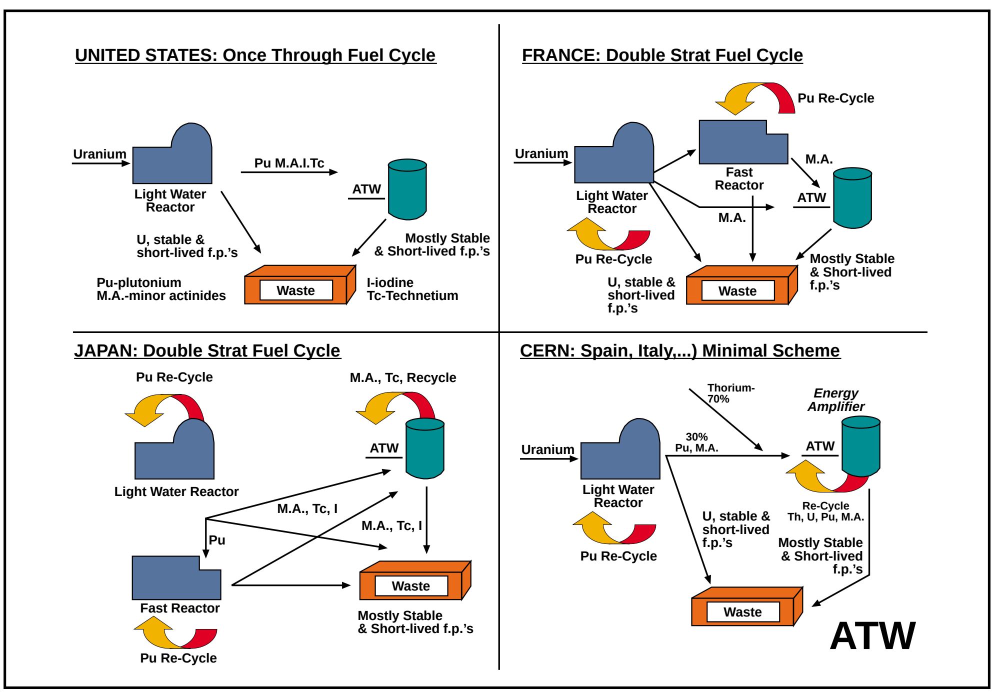

Figure 3.1. Multinational ADS Programs

The current U.S. policy is to not reprocess spent fuel. Japan, France, and Russia view plutonium as fuel and therefore an asset, which leads to a different application of ATW technology. In the "double-strata" concept in Japan, an ATW is seen as a way to optimize a transition from MOX recycle to MOX and plutonium recycle to minimize radioactive waste. ATW is used alongside liquid-metal reactors (LMRs). The French concept employs an ATW as a back-end to a mix of reactor types that includes LWRs, MOX-fueled LWRs, and breeders. A multinational European group has advocated an "Energy Amplifier" implementation of ATW; they envision the use of the waste stream from the uranium-plutonium fuel cycle as part of a means to transition to a thorium-uranium-233 cycle that may have non-proliferation and waste disposal advantages. In all cases, the use envisaged for ATW would be to destroy the TRU or minor actinide components that build up in the fuel cycle.

3.1.2 International Waste Transmutation Programs

3.1.2.1 France

The primary French objective is to develop specific technologies as an element of a global waste management strategy. The goal is to keep options open and to be able to reach a future waste management decision based on firm technical grounds. This is described as a science-based approach. To this end, France is following a national program to establish the feasibility of a large spectrum of partition and transmutation strategies.

The French waste-management scenario includes a combination of most options: LWR; LWR with MOX; fast reactors, specifically LMR; and ATW. Presently, the French level of effort is approximately 80 persons for R&D, including a large-scale international collaboration. Fuel reprocessing is based on "wet" technologies but pyrometallurgical technologies are being considered. Sodium, LBE, and helium are being pursued as coolant options.

As presently envisioned, the French ATW program may use thorium and minor actinides as fuel to produce electric power as well as waste transmutation. R&D is underway to identify fuel forms, which includes inert matrices. There are no plans to transmute technetium and iodine other than carry-over into the fuel; therefore, no separation of these elements is envisaged. A decision for construction of a demonstration plant may be made in 2006.

3.1.2.2 European "Energy Amplifier" (CERN)

The European "Energy Amplifier" is a concept that originated in CERN with cooperation between Italy, Spain, and France. The cooperation has now expanded to other European countries. The objectives of the Energy Amplifier concept are to burn actinides and produce power through a thorium fuel cycle. R&D resources are pooled between the different countries. The Energy Amplifier concept has received strong support from the European Union (EU), with the goal of helping members solve their various nuclear waste problems.

The Energy Amplifier concept is an accelerator-driven subcritical system using thorium and minor actinide fuel. The primary target and coolant option is LBE, but other cooling options using lead, sodium, or gas are being considered.

Current demonstration plans may include a small-scale fissile target by 2003. LAESA (Spain) is also proposing to build an energy amplifier demonstration facility using a 380-MeV 5-mA cyclotron with an LBE target and a 10-MW subcritical blanket.

3.1.2.3 Japan

Japan has active R&D efforts in the areas of LMRs and actinide-fueled fast-reactors. Although a long-term HLW strategy has not yet been fully defined, Japan is pursuing a combination of LWR, LWR-MOX, LMR, actinide-fueled fast reactors, and ATW. Japan has active R&D projects to examine a long-term partitioning and transmutation strategy for long-term HLW disposal. Present plans include a test facility in approximately 2009. The decision point for implementing this strategy is approximately 2030.

Japan is pursuing nitride fuels composed mostly of minor actinides. Coolants being considered are LBE, sodium, lead, and helium. Japan's processing technology is aqueous-based, but significant research into pyrometallurgical processes is being conducted.

3.1.2.4 Russia

Russia has significant projects in the area of waste transmutation concentrating mainly on plutonium disposition. To this end, Russia is pursuing a combination of LWR, LWR-MOX, and fast reactors (LMR and gas-cooled). The Russian Atomic Energy Ministry, MINATOM, has recently begun a program to investigate ATW technology.

Russia has unique expertise in the operation of LBE loops based on one of their nuclear submarine designs. Based on this expertise, they have cooperated with western ATW teams.

3.1.2.5 International Science and Technology Center Programs

The International Science and Technology Center (ISTC) has funded projects over the past several years in various technology areas (e.g., nuclear data, molten salt, and LBE) related to ATW. Currently, a number of projects are being supported. The Institute of Physics and Power Engineering (IPPE) is building a prototype LBE target that will be brought to LANL and irradiated in the proton beam at the LANSCE accelerator. This project is a joint effort between France, Russia, Sweden, and the United States. The ISTC is also funding a project on molten salt technology. The ISTC projects in ADTT are reviewed by an expert group that provides recommendations on which projects to fund and advises on work scope/direction. The contact expert group includes members from the EU, France, Germany, Italy, Sweden, Norway, Japan, and the United States.

3.1.2.6 Other Programs

Several other countries are actively pursuing research into accelerator-driven systems. Germany has recently received government funding to pursue research in this area and has built a large-scale lead-bismuth facility at Karlsruhe. Sweden has a mandate to consider alternatives to geological disposal and therefore has been an active participant in EU-funded programs as well as its own. The Czech Republic has an active program based upon the molten salt/thermal spectrum system. The Republic of Korea also is pursuing a fast neutron hybrid system.

The EU is planning a new program, the Fifth Framework program, which will start shortly. Funding is expected to be over $15M per year and will be highly leveraged by national programs. Furthermore, both the IAEA and NEA continue to sponsor international studies comparing the various features of ADS.

3.2 Near-Term Opportunities for Cooperation

Given the current international research, many opportunities exist for bilateral and multilateral cooperation on ATW R&D. Some near-term opportunities are discussed below.

3.2.1 European Union

The Fifth Framework agreement between EU countries includes significant funding for ATW research. A broad base of scientific research is envisioned with many countries participating in specific research areas supported by a combination of national and EU funding. Because the Fifth Framework agreement is currently being finalized, it is not possible to cite specific areas of research. However, informal discussions with world experts suggest that cooperation with the United States would be welcome. The amount of cooperation would depend on the size of the U.S. program.

3.2.2 France

DOE is finalizing a bilateral agreement on cooperation with the French Commissariat a l' Energie Atomique (CEA) on topic areas in the Nuclear Energy Research Initiative (NERI) program. This bilateral agreement could be amended to include specific areas of joint mutual interest, which could include 1) coolant - LBE, 2) accelerator and target design, 3) fuels and fuels testing, 4) system trade studies, and 5) basic scientific data on physics, materials, and thermal-hydraulics.

3.2.3 Japan

DOE has a long-standing history of joint/cooperative R&D programs with Japan in the area of nuclear power technologies. While joint activities have decreased significantly in recent years, a science-based U.S. ATW research program maps well into several areas of transmutation research in Japan. Areas of potential joint mutual interest could include 1) coolant - LBE, 2) accelerator and target design, 3) fuels and fuels testing, 4) system trade studies, 5) basic scientific data on physics, materials, and thermal-hydraulics, and 6) pyrometallurgical process development.

3.2.4 Organization for Economic Cooperation and Development - Nuclear Energy Agency

The NEA of the Organization for Economic Cooperation and Development (OECD) is currently conducting a partitioning and transmutation study in which the United States is participating. An ATW project in the United States may provide for broader participation in this study.

3.2.5 Russia

Russia has been working with LBE coolant technology for over 40 years. The Russian program is based primary on military applications, specifically the Alpha-class submarine program. Russia has a significant knowledge base on LBE technology and claims to have solved the key problems. A U.S. ATW program could benefit from the Russian knowledge base. Informal discussions with Russian experts have suggested that information as well as the use of several Russian facilities could be made available; however, the United States would probably have to pay for this technology transfer. Cooperation and technology transfer may be hindered because of the following issues: 1) management of reimbursement, 2) retrieval of documentation (the Alpha-class submarine information may be classified, and the data date back to 1968), and 3) qualification of materials to American Society of Mechanical Engineers (ASME) standards (the Russian steel composition for lead-bismuth usage is unique). These factors should not prevent the Unites States from investigating the potential benefits of working with the Russian scientific community on ATW technologies.

4.0 Institutional Challenges of Implementing ATW

Developing the facilities needed for an ATW system presents institutional challenges that fall into three broad categories: institutional capabilities, public acceptance, and regulatory/NEPA issues. Institutional capabilities relate to the ability of the federal government to provide the organizational and financial resources required to carry out a complex technical program extending over several decades. Public acceptance issues arise with overall policy commitment to implement ATW and the siting and operation of the required facilities. Regulatory/NEPA issues arise with the regulatory requirements for ATW activities, and requirements for development and implementation of an ATW system.

This discussion of institutional challenges deals with the two distinct phases of development and possible use of ATW technology, 1) RD&D, and 2) full-scale implementation.

4.1 Research, Development, and Demonstration

4.1.1 Program Management

Successfully implementing a program for development of an ATW system would require coordinating and integrating the activities of multiple participants and multiple DOE sites over many years. Past studies have concluded that a mission-oriented, single-purpose organization is needed to implement a radioactive waste management program extending over long periods. For ATW, a mission-focused organization may be required to manage the efforts of a wide range of participants (national laboratories, contractors, and federal agencies).

4.1.2 Regulatory/NEPA Issues

Implementation of a full-scale ATW system would be subject to the same types of regulatory requirements as other parts of the nuclear fuel cycle. To ensure that a demonstration facility demonstrates not only the technical and financial but also the regulatory feasibility of ATW, the regulatory requirements must be established, and the facility must be designed and constructed to meet those requirements.

Under NEPA, an ATW RD&D program will require a programmatic environmental impact statement covering activities through the construction and operation of a demonstration facility.

Previous studies concluded that the fundamental federal regulatory framework needed to license the facilities required for separations and transmutation technology exists. It is unclear whether current law requires a license for construction and operation of an accelerator to transmute waste. This depends on whether such an accelerator would be considered a "production" or "utilization" facility, both of which require licenses under the Atomic Energy Act (this dilemma might be moot for the deployment-driven ATW system because generation of electricity is a central part of the concept).

Previous studies also concluded that an accelerator used to transmute waste is considered to be a utilization facility if neutron bombardment of the waste produces heat that is used to generate power. Under current NRC regulations, a utilization facility is defined as "any nuclear reactor other than one designed or used primarily for the formation of plutonium or uranium-233" (10 CFR 50.2). A revision to these regulations might be required to cover ATW transmuters.

Repository performance standards will be used to define ATW performance objectives. Near-total destruction of all of the radionuclides of concern may be neither feasible nor necessary. Decisions must be made about how much reduction is required for which radionuclides. Improving repository performance to levels higher than the regulations require might be difficult to justify if achieving those levels would require large expenditures and would impact operations. An acceptable balance would have to be found between improved long-term performance and increased operational costs and impacts.

International collaboration in developing ATW technology using high beam-power accelerators could raise export control issues. Diversion of materials for use in nuclear weapons is a concern when a technology is used that involves special nuclear materials (plutonium). The DOE has determined that existing DOE regulations implicitly cover exports of accelerator technology to produce special nuclear materials and is now determining whether to make this coverage explicit.

4.2 Deployment

4.2.1 Management Resources

Full implementation of an ATW system to treat spent fuel produced by power reactors would require a major commitment of management resources and funding over many decades. Past studies and experience suggest that the necessary institutional capabilities need to be developed. It is unlikely that the private sector would implement a waste transmutation system on its own without incentives. Earlier studies of separations and transmutation systems concluded that the federal government would have to play the primary role in organization, management, and funding of any such system. The fundamental challenge would be to ensure that adequate and stable management and financial resources are devoted to the task over several decades.

4.2.2 Funding Approach

A major institutional challenge for full-scale implementation of ATW would be ensuring stable funding over an extended period of time, which would benefit by some independence from the annual pressures of the federal budgeting process. Stable funding would be needed since delays could increase costs and erode public confidence and because only partial completion of waste transmutation could increase waste disposal problems. If an ATW system is deployed, revenues from the sale of ATW-generated electric power could eventually be dedicated to reimbursement of developmental and implementation costs.

The Nuclear Waste Fund, as it is presently structured, could not be used for separation and transmutation since the Nuclear Waste Policy Act of 1982 limits its use to:

- Development of geologic repositories, monitored retrievable storage facilities, or test and evaluation facilities constructed under the Act.
- RD&D activities directly related to the Act.
- Transportation, treatment, or packaging of spent fuel or HLW to be disposed of in a repository, stored in a monitored retrievable storage site, or used in a test and evaluation facility.

A substantial part of the cost of implementing an ATW system would be expected to be offset by the sale of byproduct electricity. Marketing the electricity presents several issues that must be addressed. First, accelerators currently do not have the same operational reliability as standard electricity generating plants. The reference ATW station might potentially generate about 2,200 MWe (net) for sale—the capacity of two large nuclear power reactors. The station capacity would depend on the continued operation of the two accelerators. Generating such a large single-source capacity continuously could be a significant issue when it is connected to the distribution grid.

Another consideration is the possible conflict between the objectives of revenue-creation and waste-minimization. The principal objective of an ATW system would be the efficient destruction of long-lived radionuclides for waste management rather than maximization of revenues from the sale of the resulting electricity. An institutional structure would need to be established to ensure that near-term considerations do not create pressures to focus more on revenue production than on destruction of TRU.

Ensuring that the revenues from the sale of electricity will contribute to funding for the system is another challenge. Experience with federal trust funds have shown that ATW power sales revenues may not necessarily be treated in the Federal budget process as offsets to program costs.

4.2.3 Regulatory/NEPA Issues

State and local governments are becoming increasingly involved in regulatory activities, introducing additional uncertainties into the future regulatory requirements for deploying an ATW facility. Siting, licensing, and environmental impact statements (EISs) would be required for the eight ATW stations in the deployment-driven approach. Under NEPA, EISs would be required for plant construction and operation in the event that ATW stations were deployed.

4.2.4 Public Acceptance Issues

4.2.4.1 Acceptability of Reprocessing Spent Fuel

Whether to reprocess spent fuel to recover and reuse plutonium has been the subject of contention since the 1970s because of concerns about potential proliferation of nuclear weapons. A recent DOE decision to dispose of surplus weapons plutonium by irradiation in MOX fuel was opposed by some on the grounds that it would tend to promote reprocessing and plutonium recycle, showing that the concerns of opponents have not abated despite the continued use of reprocessing and recycle in other countries. Proposals to transmute selected radionuclides in spent fuel would probably find similar opposition because they involve processing of the spent fuel and separation of plutonium and other minor actinide elements (americium, cerium, and neptunium). The present ATW concept does not separate weapons-usable fissile materials at any time during the process. In addition, the reference ATW facility would be designed so all separations and fuel fabrication activities for each ATW station would be contained in one building. Spent fuel would be delivered to the ATW station, and only waste from the transmutation process would leave. The ATW facilities would be subject to full IAEA safeguards.

4.2.4.2 Other Issues

The ability to implement a concerted ATW effort over several decades ultimately would depend on developing and sustaining a national consensus about the importance of that effort. Literature on public opinion suggests that concern about nuclear waste and potential diversion of materials for use in weapons is a primary reason for opposing nuclear power, and transmuting spent fuel before disposal may not reduce public opposition and may raise additional issues such as processing spent fuel, siting of eight ATW stations, and transportation.

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5.0 Impacts on the High-Level Radioactive Waste Repository Program

For more than 15 years, DOE has been studying a site at Yucca Mountain, Nevada, to determine whether a decision on the suitability of the site for further development may be made. A repository would be used to permanently dispose of spent fuel from power reactors, DOE spent fuel, and HLW resulting from weapons activities. DOE believes that Yucca Mountain is a promising site and that work should proceed to support a decision in 2001 on whether to recommend the site to the President for development as a repository. Although current assessments of repository performance are encouraging, more work is needed before the site can be recommended and a license application for construction can be submitted to the NRC. For the Yucca Mountain site to be recommended, DOE needs to demonstrate that a repository can be designed and built that would protect public health and safety and the environment for thousands of years. A repository program should be continued even if an ATW program were deployed because it will also be required for disposal of the waste from ATW as well as the HLW not treated in the ATW program.

The current repository design concept has a capacity of 70,000 t of radioactive wastes, including 63,000 t of spent fuel, 2,333 t of DOE spent fuel, and 4,667 t of HLW. Extensive studies from this repository program provide insight into the process and potential problems in the design, licensing, construction, operation, and long-term safety of a repository. Based on this evolving understanding of geologic disposal, the potential benefits from ATW can be assessed. Benefits from treatment of spent fuel from power reactors using ATW technology could include the following:

- Reduced inventory of hazardous materials with favorable impacts on repository performance.
- Improved confidence in repository performance.
- Design flexibility, simplicity, or optimization.

5.1 The Current U.S. High-Level Radioactive Waste Program

The U.S. repository program is based on the Nuclear Waste Policy Act of 1982, as amended, that requires the packaging and burial of DOE spent fuel, HLW, and spent fuel from power reactors. The standards and regulations require that the natural and engineered barriers work as a system to achieve health and safety requirements. The waste forms and waste packaging (engineered barriers) necessary to meet EPA and NRC health and safety requirements must be highly resistant to corrosion and mobilization of waste materials. Current regulations also require that waste placed in a repository be retrievable for 50 years after the start of disposal operations.

In the current design concept, a proposed repository would place the radioactive materials in waste containers and entomb them. For a potential repository at Yucca Mountain, emplacement could be in tunnels 300 m below the ground surface. Given current waste inventory, approximately 11,000 waste packages would be placed in tunnels covering an area of about 400 hectares. The waste packages would be designed to last thousands of years to provide long-term isolation of the radioactive materials from the environment. The preliminary repository design also takes advantage of the desert environment and geologic features of Yucca Mountain (Figure 5.1).

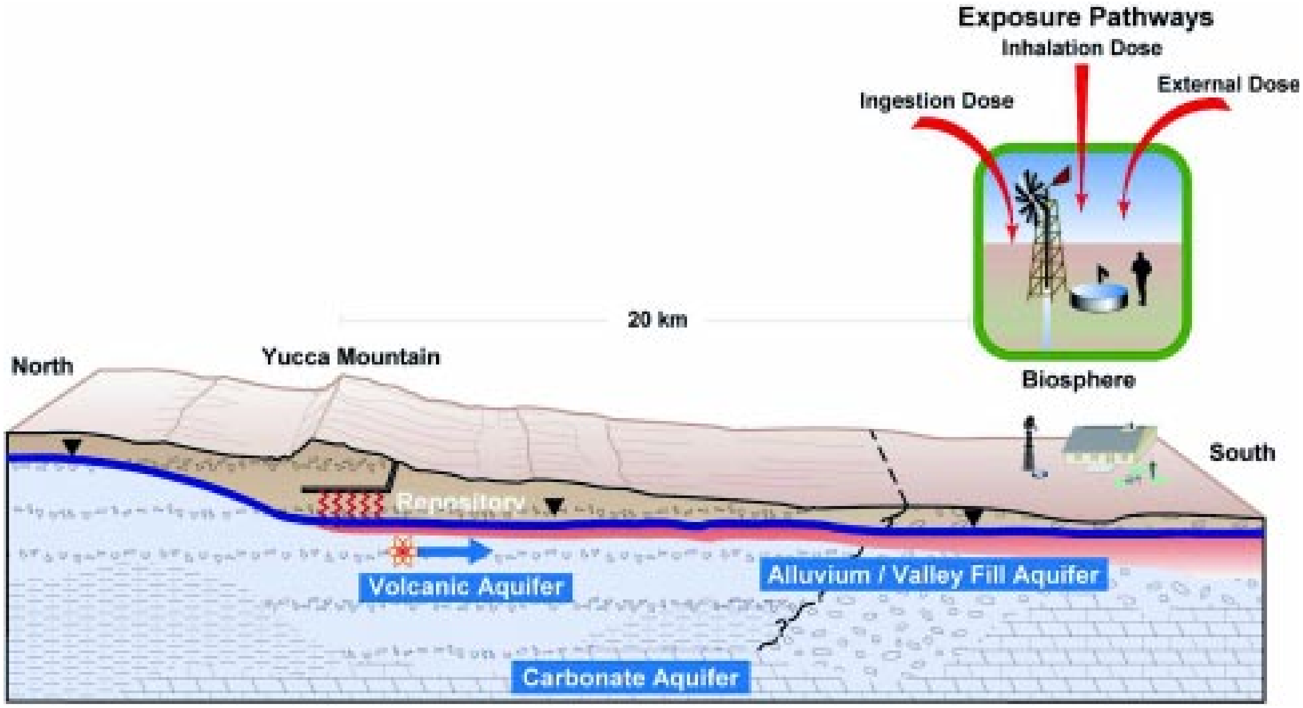

Figure 5.1. Exposure Route for Humans from Radioactive Materials Placed in a Repository Such as Yucca Mountain (Artist's Conception)

5.2 Potential Effect of ATW Processing on Repository Long-Term Performance

The DOE recently completed the *Viability Assessment of a Repository at Yucca Mountain* (DOE/RW-0508, 1998) (hereafter referred to as the Viability Assessment.) This document presented to Congress, the Administration, and the public an assessment of how a repository might work at the Yucca Mountain site. Estimates of the long-term repository performance were developed and reported for a wide range of assumptions. Stochastic models were used to address the inherent uncertainty in predicting performance for 10,000 or more years. A special model run, called the base case, was also reported. This model run uses the mean, or expected value, of the stochastic input parameters and addresses disposal of 70,000 t of radioactive materials.

A comparison of the repository performance with and without ATW processing is provided in Figure 5.2. The two curves represent the dose rate (millirem/year) to an adult living in the Amargosa Valley 20 km south of the repository who uses groundwater and eats crops that may contain radionuclides from the repository. The base case performance is taken from the Viability Assessment. Repository performance, assuming ATW processing on the 63,000 t of spent fuel but no processing of DOE spent fuel or HLW, is also provided.

The following major assumptions were made in evaluating repository performance assuming ATW reprocessing:

- The dose rate estimates use the same parameters as used in the Viability Assessment.
- The size and thermal characteristics of the repository are the same as for the Viability Assessment base case.

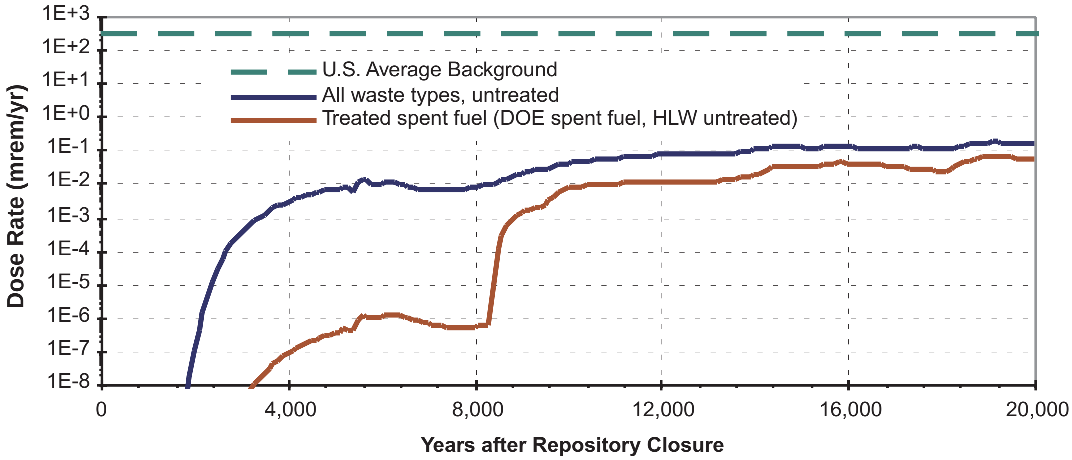

Figure 5.2. Individual Dose Rate (Adult, 20-km Distance, All Exposure Pathways) Comparison for the First 20,000 Years After Repository Closure (the four-orders-of-magnitude difference between the two curves during the first 8,000 years is the product of two reductions, each by approximately a factor of 100: 1) for the transmutation of iodine and technetium, and 2) for the change from civilian spent fuel to ATW process waste. The step change thereafter reflects failed defense waste packages.)

- Only commercial spent fuel is processed using ATW technology (2,333 t of DOE spent fuel and 4,667 t of HLW is not treated by ATW technology).
- The ATW process removes 99.9% of the TRU from the spent fuel.
- The ATW process removes 95% of the technetium-99 and iodine-129 from the spent fuel.
- The dissolution characteristics of the ATW waste forms are the same as the characteristics of the HLW glass waste form because no ATW data are available.

The assumptions for the parameters and thermal characteristics of the repository were made in order to apply the performance assessment model that was used for the Viability Assessment. If the ATW is successful, thermal conditions of the repository would change due to actinide removal from ATW waste; however, this effect was not evaluated in the study. There is also considerable uncertainty with respect to the amount of technetium and iodine that can be removed during separations as well as the amounts that can be transmuted. Any decrease in the percentage of these isotopes removed from the waste would cause a proportional increase in the lower curve of Figures 5.2 for about the first 8,000 years.

Using these assumptions, the dose rate from the repository if ATW processing were performed is lowered by about four orders of magnitude out to 8,000 years after repository closure. The step change in the ATW line in Figure 5.2 at about 9,000 years comes from assumed earlier failures of defense waste packages. After that time, the dose rate is dominated by DOE spent fuel and HLW and would be reduced by only about a factor of five at 20,000 years after repository closure. The ATW repository performance improvement rises to a factor of 10 and would improve only a small amount after 20,000 years, as shown in Figure 5.3.

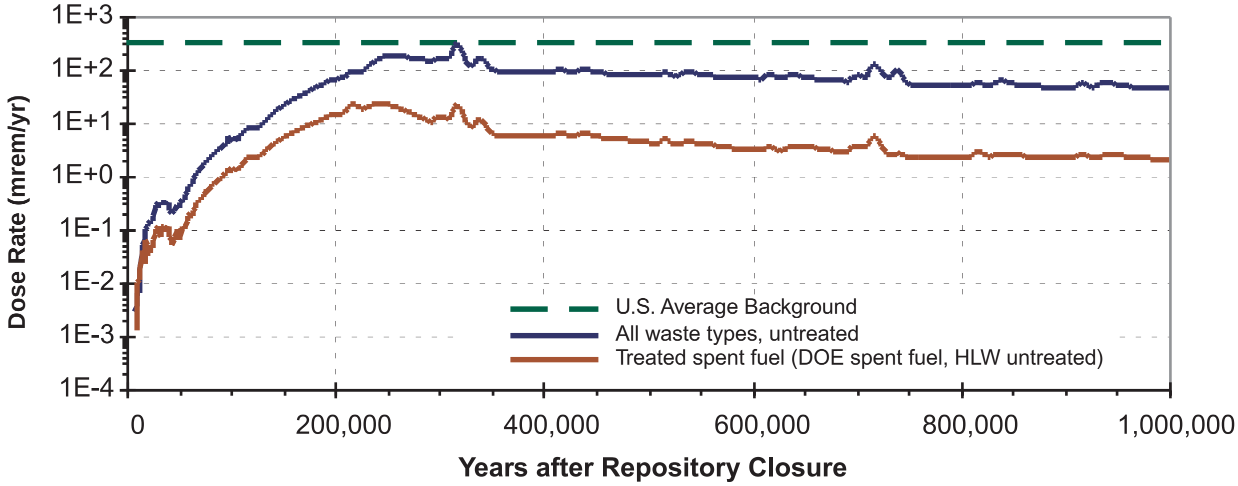

Figure 5.3. Individual Dose Rate (Adult, 20 km Distance, All Exposure Pathways) Comparison for the First Million Years after Repository Closure

If ATW processing were performed, the zircaloy cladding would be removed from spent fuel (zircaloy cladding is present in 99% of the spent fuel). In the base case analysis, cladding is assumed to provide a long-term barrier to radionuclide movement. The ATW waste form is assumed to be placed in zircaloy canisters with corrosion resistance equivalent to that of zircaloy fuel cladding.

If ATW is successfully demonstrated at the assumed high level of efficiency, Figure 5.4 shows the hypothetical effect on repository performance of only commercial spent fuel after ATW processing. Figure 5.4 also shows the repository effect without ATW processing. However, the reduction of dose from commercial spent fuel only translates into a one-order-of-magnitude reduction in peak dose compared to a respository that includes DOE spent fuel and HLW (Figure 5.3). The early portion of the dose curve, i.e., for about 50,000 years, is due to the release of iodine and technetium. After that, the dose is dominated by neptunium, and the peak dose on both curves in Figure 5.4 is primarily from neptunium.

5.3 Proliferation Risk

The most complete method for ensuring that fissile material is never used for nuclear explosives is to transmute it into something that is not fissile. Although plutonium-239 and uranium-235 comprise the bulk of the fissile inventory in about equal quantities, depending on initial enrichment and burnup of the fuel, plutonium-239 is the main proliferation and diversion concern. Some minor actinides are also fissile and require safeguarding. Spent fuel is considered unattractive for diversional proliferation due to the requirement to separate fissile material. Deployment of an ATW technology would eliminate this concern. At the same time, ATW technologies themselves would become a potential proliferation/diversion issue. The present ATW concept does not separate pure plutonium from the other TRU at any time during the processing.

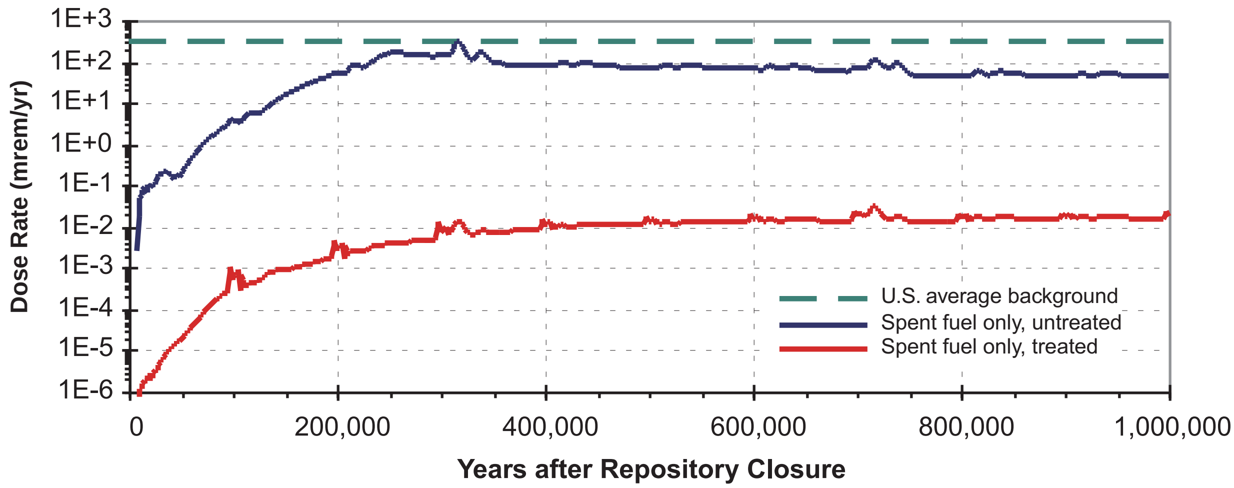

Figure 5.4. Individual Dose Rate (Adult, 20-km Distance, All Exposure Pathways) Comparison for the First Million Years After Repository Closure for a Repository Containing Only 63,000 t of Spent Fuel or ATW Waste (the four-orders-of-magnitude difference between the two curves is the product of two reductions: 1) a factor of 1,000 for reduction in TRU, and 2) a factor of ten for change in waste form and depletion of TRU in failed packages.)

5.4 Other Benefits

ATW has the potential for benefits in the management and disposal of spent fuel and potentially other radioactive wastes. Development of ATW technology also has the potential for benefits beyond the direct goal of transmutation of waste.

5.4.1 Criticality Risk

The spent fuel inventory includes fissile materials. Criticality control is one of the design constraints on the waste package in a repository. ATW removes most of the fissile nuclides from the waste, significantly reducing any risk of criticality.

5.4.2 Customized Waste Forms

A benefit to repository performance comes from the separation processing used in the ATW system. While spent fuel is reasonably resistant to corrosion and dissolution, it was designed primarily for several years of nuclear reactor operation, not for millennia of radionuclide isolation in a geologic repository. Processing each waste stream from ATW into a chemical and physical form optimized for that waste may reduce the release rate of radionuclides from the repository. An example would be putting the small amount of residual technetium and iodine into dissolution-resistant alloy, mineral or ceramic forms with dissolution rates lower than uranium oxide or glass. This could reduce the release rate for highly soluble nuclides and result in reduced dose rates.

Custom waste forms also provide flexibility in repository and waste package design. Many design decisions are driven by the need to accommodate intact spent fuel assemblies. As contrasted with intact spent fuel, waste package size, shape, weight, and thermal limits could become variables with ATW waste. Added flexibility could also be realized for repository design and operations.

The technical basis documents supporting the Viability Assessment address uncertainties remaining in data, models, fundamental understanding, or details of implementation in performance assessment of a geologic repository. For example, in the area of waste forms, uncertainties in the following areas potentially requiring further work are discussed:

- Very long-term cladding performance.
- Water contact processes.
- Wide range in radionuclide solubilities, and thus mobilization rates.
- Secondary phase formation in uranium oxide dissolution
- Colloid formation and transport
- Diffusive transport processes.

The result of ATW technology in reducing inventory and customizing waste form could address all of these uncertainties in beneficial ways. Some uncertainties could be eliminated (such as cladding and uranium oxide secondary phases) and others limited in performance impact (such as solubility and colloid formation).

5.5 Schedule Impacts

The DOE planned repository development activities (as of FY 1999) include completing the EIS for site selection in 2000, making a decision in 2001 on recommending the site for further development, and submitting a license application to the NRC in 2002. Should the site be licensed and constructed, it is expected to receive waste for emplacement by 2010. Emplacement of spent fuel in the repository would be completed in 2035, although the repository would contain only 63,000 t of the projected 87,000 t of spent fuel. Under the deployment-driven schedule for ATW (see Appendix), the first ATW station could start operation in about 2035.

Thus, repository development and waste emplacement activities could be completed before the first ATW station would start operations. Because ATW stations will require a repository for disposal of ATW waste forms, from a waste management perspective it is appropriate for the current repository development program to proceed as planned.

5.6 Impacts on Repository Radiological Safety

Occupational radiological safety of a repository was not evaluated for an ATW scenario. However, if the repository were filled before an ATW system were available and spent fuel were retrieved for ATW processing, the additional activities would result in some additional radiological exposure and occupational safety risk. In addition, risk to the public would increase by a small amount as a result of shipping the spent fuel and ATW waste to and from any ATW station not co-located with the repository.

6.0 Benefits to Other Programs

The development of ATW technology would further the development of other technologies by enhancing the RD&D and deployment of technologies being developed by science and technology-based programs worldwide. Below are a few examples of these programs and the benefits that could accrue.

6.1 Energy Production

A benefit from an ATW system would be the production of electrical energy. The conceptual ATW campaign has the potential to provide over 800 GW-yr of electricity. The potential retail market value of this electricity is as high as $300B (in undiscounted 1999 dollars). This electricity represents about 30% of the electricity generated by the nuclear reactors that originally used the fuel. It has been suggested that such an individual power station would be a candidate for coupling with advanced energy options such as hydrogen production, hydrogen/fuel cell storage, pumped storage or superconducting distribution. ATW produces this energy without requiring "new" fuel by using the residual energy potential of plutonium and minor actinides in the spent fuel.

6.2 Isotope Production

ATW technology represents a potential source of isotopes for medical, industrial, and research purposes. An ATW system has the potential for producing a wide range of isotopes. ATW could produce other useful isotopes as a byproduct via spallation and neutron capture, such as the cobalt-60 used widely to sterilize medical instruments. Other isotopes could also be produced by adding other target materials. The medical isotope market is currently dominated by a small number of isotopes and medical procedures. However, many new procedures are undergoing pre-clinical studies and clinical trials, and many of these rely on so-called "designer isotopes." The ATW capability for producing such isotopes has high potential because of its full range of capabilities for nuclear transformations. If needed, production of isotopes for thermal sources (e.g., power supplies for space applications) could be performed with some impact on ATW throughput. Although ATW could be modified to produce tritium, the Russians have indicated they would not agree to having their LBE technology used for this purpose.

6.3 Intense Neutron Source

Neutrons are excellent material probes, and accelerators have been used to drive spallation neutron sources for decades. The pulsed nature of many accelerators allows researchers to use event-timing techniques that are impossible with continuous streams of neutrons. Thus, historically, accelerators have been used for delivering pulsed streams of neutrons, and reactors have been used when large quantities of neutrons are desired continuously.

Accelerator-driven systems with subcritical neutron multiplication can provide strong neutron sources with flexible time pulsing characteristics that would enable new regimes of operation. A side benefit of source-driven neutron-multiplying systems would be the production of high fluxes of neutrinos and neutrons of a spectrum well-suited for fusion materials development.

6.4 Nuclear Technology Development

An indirect benefit from ATW development and deployment could come in the form of advanced technology and international participation in advanced nuclear technology:

- Accelerator Technology - The U.S. would continue its leadership role in high-current/high-power accelerator technology, with likely improvements in cost-effectiveness and reliability.
- Separations Technology - Deployment of pyrometallurgical processing at the scale of ATW would bring this technology to the forefront and demonstrate weapon proliferation/diversion-resistant options for nuclear fuel cycles.
- Materials and Coolant Technology - Materials development on the ATW program would advance the state of knowledge and benefit other programs and industries.
- Neutron Science Research - ATW development would provide unique opportunities for intense neutron source research.

6.5 Maintaining Core Competency in Nuclear Technology

The ATW program would provide an opportunity for DOE to address important issues of waste management and electrical energy supply. In addition, a science and technology program on issues of energy, ecology, and waste management may increase the interest of students to pursue careers in science, energy, and technology. This would strengthen the U.S. scientific base in the future and may help slow the current U.S. decline in engineering students.

7.0 Life-Cycle Costs for a Deployment-Driven ATW System

This section presents in summary form, an analysis of the life-cycle costs associated with a deployment-driven ATW system (described in the Appendix) that satisfies the congressional mandate for such an analysis. The life cycle of the system analyzed would transmute TRU and technetium and iodine products from civilian spent nuclear fuel and generate electric power. Details of the analysis are found in the life-cycle cost report on the attached CD-ROM. These life-cycle costs include the up-front technology RD&D necessary to ensure technical success: the design, construction, and operation of the research, demonstration, and production facilities (including waste treatment and disposal) and the decontamination and decommissioning of these facilities at the ends of their useful lives.

7.1 System Description and Implementation Scenario

The system implementation scenario used as the basis for this total system life-cycle cost estimate represents a RD&D and implementation program that achieves deployment of the full complement of ATW stations. This schedule and scenario may not reflect the sequence and schedule of activities that would actually be followed if an ATW program were authorized. While this scenario is a viable approach and represents initial thinking of technical experts, it is only one of a number of possible descriptions and scenarios that could be considered. Other viable descriptions and scenarios could result in significantly higher or lower estimated total system life-cycle costs, depending on the levels of funding available over time, the assumed characteristics of the nuclear power industry in the future (with or without a new generation of LWRs, with or without a strong ALMR component of the industry, etc.).

The total system life-cycle cost comprises the following principal cost elements:

- Initial research, development, and prototype activities (about an 8-year program).
- Design, construction, and operation of demonstration facilities (about a 20-year program).
- Design, construction, and operation of production facilities (about a 90-year period, as discussed below) for which principal cost elements of the production period include:
  - 1 spent fuel retrieval and transport function for spent fuel from storage sites to the spent fuel processing facility and to return residual uranium, fission products, and fuel assembly hardware to storage/disposal site(s).
  - 1 transport and disposal function to deliver separated uranium and other low-level wastes to low-level waste disposal.
- 8 ATW stations, with each station consisting of:
  - 2 accelerator units.
  - 1 spent fuel processing facility to separate uranium and fission products from the spent fuel, process the separated actinides and special fission products (technetium and iodine) into irradiation assemblies, and treat and package the residual uranium, fission products, and fuel assembly hardware for disposal.
  - 8 transmuter units, forming 4 power blocks of 2 transmuters each.
  - 4 electrical generation units and 1 station switchyard.

– 1 ATW fuel unit for preparation/fabrication/recycle/refabrication of ATW fuel and for target processing/fabrication/recycle refabrication, including waste treatment and packaging.

– 1 waste transport and disposal function for ATW radioactive wastes — ATW station to the disposal sites and emplacement.

The schedule for this rapid implementation scenario, including RD&D and deployment of the eight ATW stations is shown in Figure 7.1, with the RD&D activities completed in about the twenty-eighth year, and the completion of the transmutation of the expected inventory of LWR spent nuclear fuel (the no-new-orders case) in about 118 years. The deployment bar for Station 1 shows the period for the low-power demonstration activities using Transmuter 1 and the times at which Transmuter 2 and Power Blocks 2, 3, and 4 come online to produce electricity.

Figure 7.1 also shows the buildup and decline of spent fuel inventory (t), spent fuel volume (m^3), buildup of ATW HLW (m^3), and the cumulative generation of electrical power in gigawatt-years over the lifetime of the postulated rapid implementation scenario ATW system.

The life cycle of a typical station would extend over about 76 years, from start of design to final decommissioning. The post-demonstration life-cycle duration for the eight-station system, from initial power operation to final shutdown of the last power block would be about 90 years, during which time about 87,000 t of spent fuel would be processed and transmuted and the residual radioactive wastes returned to the geologic repository and a low-level waste disposal site and emplaced.

The costs for completion of the postulated rapid implementation scenario program, including program integration costs, licensing costs, and waste retrieval, transport, and disposal costs, are summarized by major technical components in Table 7.1.

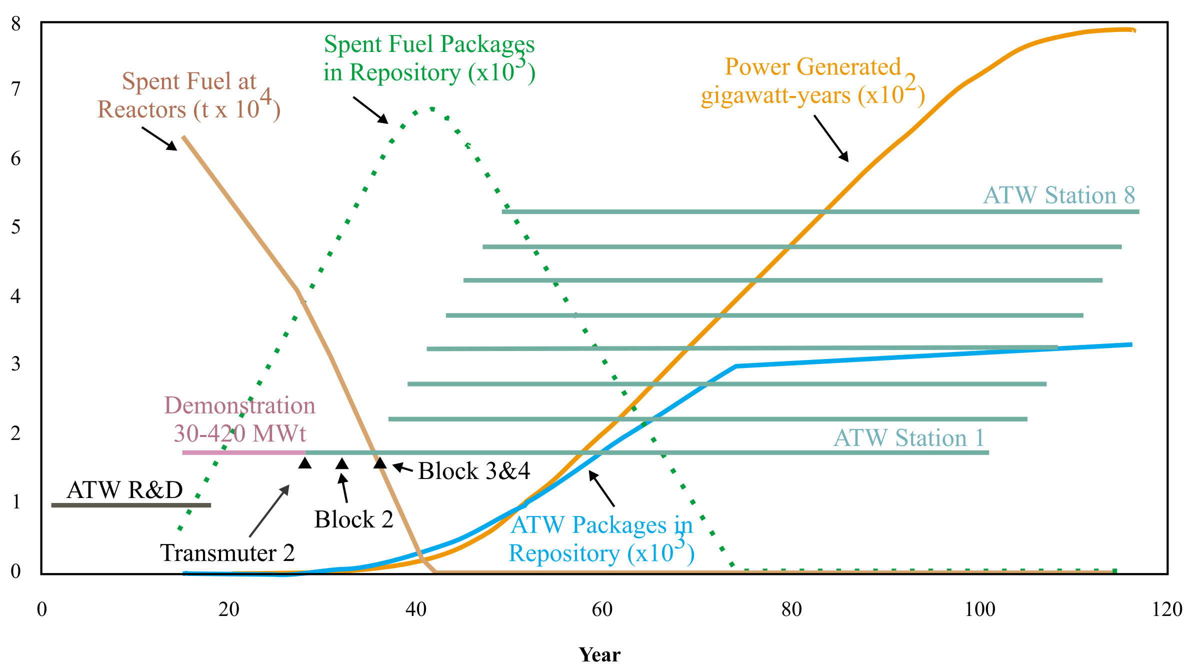

Figure 7.1. Integrated Schedule for RD&D and Deployment of ATW Technology

7.2 Time Distribution of Total System Life-Cycle Costs and Electrical Credits

The time distribution for the estimate system life-cycle costs and potential life-cycle credits for electricity sold at 43 mills/kWh are illustrated in Figure 7.2. The selection of 43 mills/kWh was based on an estimate by the Electric Power Research Institute (EPRI) concerning the electricity sales price at which nuclear power stations would be competitive with central power from fossil fuels. The values in Table 7.1 and Figure 7.2 are in undiscounted 1999 dollars. The time delay in income compared with expenses and possible discount rates will tend to decrease the off-set that power sales provide for ATW implementation costs. Electric sales at 43 mills/kWh and a 0% discount rate would indicate sales covering the costs, and a 3% discount rate would indicate sales covering 70% of the costs. Commercial discount rates would be higher and the coverage lower.

7.3 Uncertainty Analysis

The detailed life-cycle report contains an uncertainty analysis based on the various components of the total cost and the estimated uncertainty in each. The analysis showed that the production cost and its estimated uncertainty range lie within the range of current production costs of U.S. investor-owned electric utilities.

Table 7.1. Total Deployment-Driven System Life-Cycle Costs by System Phase and System Element (Billions of Undiscounted 1999 Dollars)

Element	R&D	Demonstration	Implementation			Total[a]
			Capital	Operating	D&D	
Accelerators	0.17	3.0	11.0	44.0	0.6	59.0
Transmuters	1.0	2.0	30.0	49.0	3.0	86.0
Separations	0.5	2.0	9.0	41.0	1.0	53.0
ATW Fuel Fabrication	0.0	0.6	2.0	41.0	0.2	44.0
Site Support	0.0	1.0	1.0	31.0	0.1	33.0
Retrieval/ Transportation/Disposal	0.0	0.1	0.0	4.0	0.0	4.0
Integration	0.07	1.0	0.0	0.0	0.0	1.0
Subtotals	2.0	9.0	54.0	210.0	5.0	279.0[b]

[a]Totals may not be the exact sum of the columns due to rounding.

[b]Electric sales at 43 mills/kWh and a 0% discount rate would indicate sales covering the costs, and a 3% discount rate would indicate sales covering 70% of the costs. Commercial discount rates would be higher and the coverage lower.

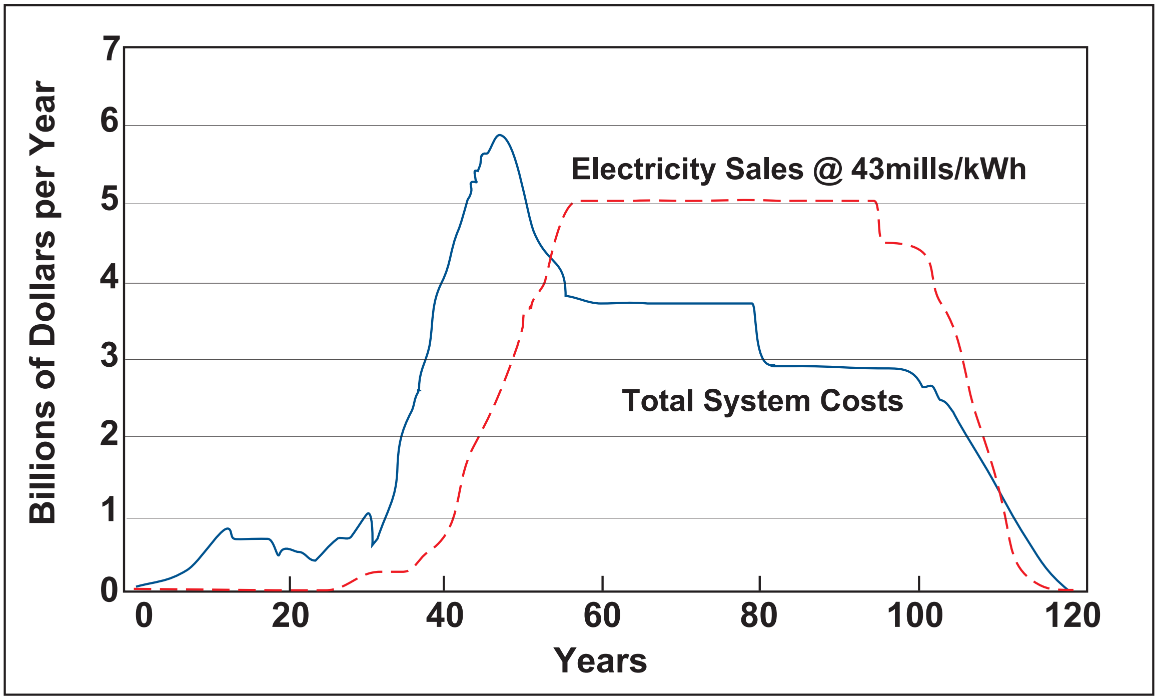

Figure 7.2. Annual Undiscounted (1999 Dollars), Total System Costs and Electricity Credit as a Function of Time

Appendix — Deployment-Driven ATW System Implementation

A.1 Deployment-Driven ATW Scenario

A.1.1. Background

An initial roadmap was developed for an aggressive "deployment-driven" ATW campaign to establish reasonable sequencing of R&D, demonstration, and deployment activities, to estimate life-cycle costs, and to help size ATW components. This scenario is only one of a number of possible scenarios that could have been considered. This deployment-driven scenario is based on the following assumptions — assumptions that are not unique, but provide a clear definition of scope and time frame:

- ATW is developed rapidly to achieve an earliest possible implementation (full funding is available and institutional delays are minimal).
- No new commercial nuclear power reactors are built.
- ATW units are built and operated over a period of 90 years to treat 87,000 tonnes (t) of spent fuel.
- Costing data can be based on nuclear technology currently available for which a suitable level of experience at prototypical, demonstration, and/or deployment stages has been accumulated.

A.1.2. Deployment-Driven System Overview

During its operating lifetime, a typical ATW station would process about 175 t/yr of uranium dioxide from spent fuel (see Figure A.1.1). Eight ATW plants would be required to process the projected inventory of about 87,000 t of spent fuel. The functions of a typical ATW station are illustrated in Figure A.1.1. The separation process would start with an aqueous process to separate out the uranium. Iodine would be isolated during this step. The result would be largely transuranic (TRU) oxides that would be moved to the pyrometallurgical separations process. The next separations step would be oxide-reduction to convert the oxide to metal. In the final step, the TRU would be separated from the remaining fission products.

Approximately 166 t of uranium would be obtained each year from processing the spent fuel at a single station (the total from all eight stations would be about 10% of the existing depleted uranium in the U.S.). The processing of the 175 t of spent fuel would also generate about 36 cubic meters/yr of ceramic waste and 6 cubic meters/yr of metal waste containing fission products (6.1 t/yr) that are either stable, short-lived, or possibly longer-lived but would not contribute significantly to dose, and small amounts of TRU. Noble gases, carbon-14, and other volatile fission products contained in the spent fuel would either be released under controlled and approved conditions or treated and placed in approved waste forms for disposal. The quantities of these materials have been managed in power reactors and/or government facilities for decades. These waste forms would go to a repository for long-term disposal. The TRU, about 1.82 t/yr, would be blended with zirconium to form ATW fuel assemblies. It is assumed that about 22% of the TRU content would be fissioned per pass through an ATW transmuter. The technetium (7.4 kg/yr) and iodine (2.1 kg/yr) would be formed separately into target assemblies or other waste forms.

The throughput of TRU is derived directly from the fission heat rate of the blanket. Therefore, the 1.82 t/yr of TRU corresponds directly to the amount of fission required for the eight subcritical transmuters to generate 6,720 MWt (including about 100 MWt of beam power). Power production assumes 37% thermal efficiency that converts to 2,486 MWe. After 60 years of operation at each ATW station, virtually all of the TRU will have been fissioned. Eventually, the small residual inventories of TRU from the last ATW station would be incorporated into durable ceramic waste forms and placed into a high-level waste (HLW) repository.

A.2 Deployment-Driven R&D Program

The summary roadmap that identifies the key technical issues and the schedule of major activities and key decisions for the first eight years of the deployment-driven implementation is shown in Figure A.2.1. Detailed roadmaps developed by each Technical Working Group (TWG) are given in the following subsections. The roadmap builds from research, development, and demonstration (RD&D) conducted in other countries for many years and related work being conducted in other programs in the U.S. The current R&D needs were identified after evaluating the results of these other programs and provided the basis for the detailed

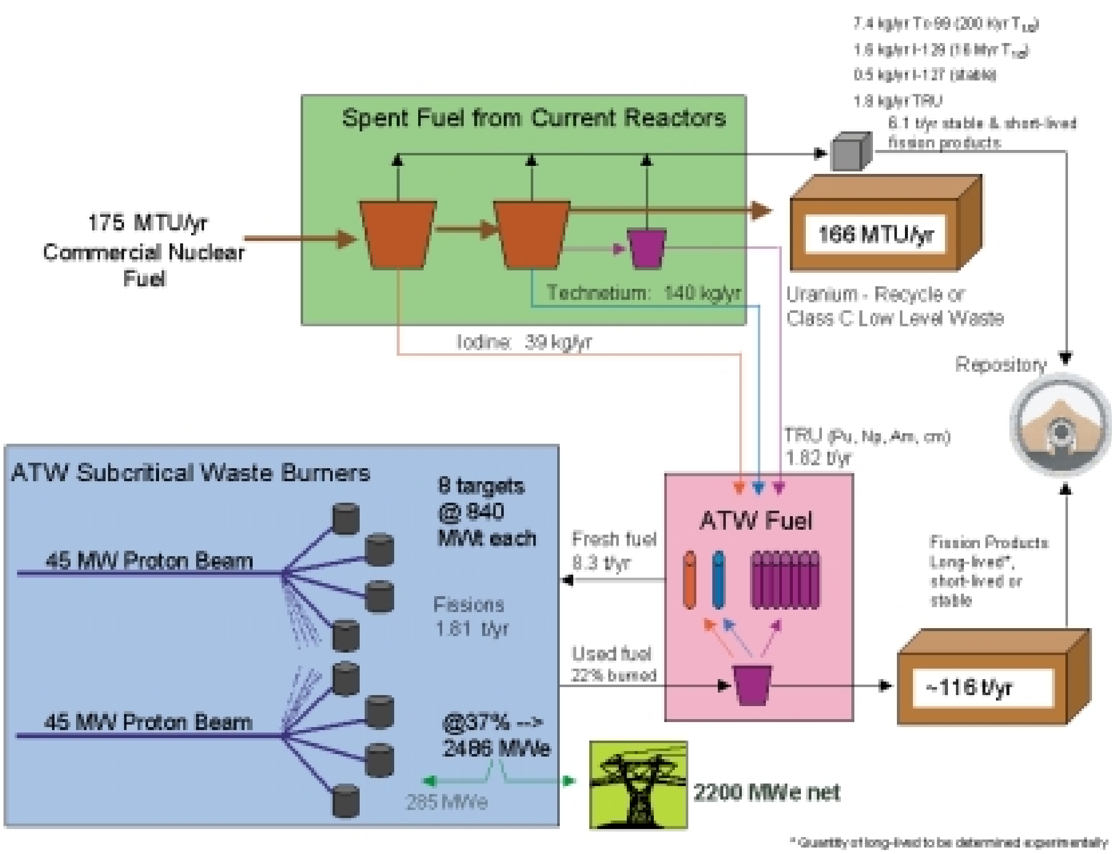

Figure A.1.1. Annual Equilibrium Operation of a Conceptual ATW Station Based on Average Composition of Deployment-Driven Scenario Spent Fuel

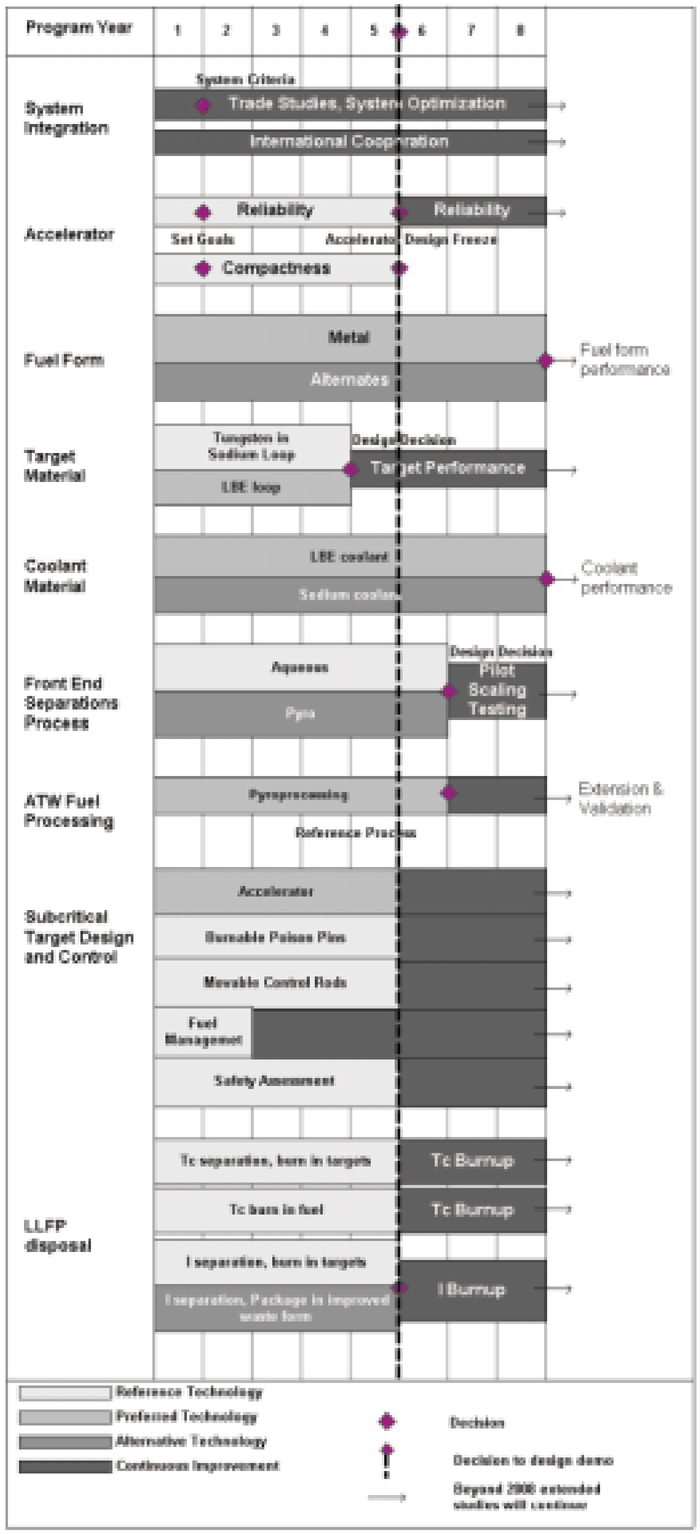

Figure A.2.1. Summary Deployment-Driven ATW Technology R&D Roadmap roadmaps developed by the TWGs (see the detailed TWG reports on the CD-ROM accompanying this report). The three technology-based TWGs, in collaboration and cooperation with the ATW steering committee, identified a set of scenario component options. Based on the technical options, economics, and other factors, a deployment-driven scenario was developed.

Although the deployment-driven scenario was used to identify and size ATW system components, the scenario did not cost-constrain the consideration of alternatives or the schedule for pursuing R&D to support decisions regarding which alternative should be developed and demonstrated. The Summary Roadmap indicates a basic R&D time period through the eighth year of the program. However, sufficient information is expected by the fifth year to support a design decision for development of an integrated demonstration facility. This period includes conduct of basic R&D and development and testing of components at a variety of locations at existing U.S. and/or international facilities. Following the basic R&D period, continual evaluation and validation of components would be performed to optimize the system, improve reliability, and prepare for integrated testing and demonstration. The key technical decisions associated with this roadmap are shown in Table A.2.1.

The summary cost profile for this R&D program is shown in Figure A.2.2. The total cost is estimated to be about $1.8B over the period leading up to, but not including, the demonstration facilities and activities.

Table A.2.1. Key Decisions for Summary Roadmap

Item	Key Decision	Program Year
1	Selection of Linac Components	1
2	Selection of ATW Target Materials	4
3	Selection of ATW waste form(s)	5
4	Target Design and Control	5
5	Detemination of ATW Technology Feasibility	5
6	Selection of the Spent Fuel Reference Processes	6
7	Cavities/Cryomodules/rf/Injector	6
8	Selection of ATW Spent Fuel Reference Processes	6
9	Selection of ATW Fuel Form	8
10	Selection of ATW Coolant	8
11	Detemination of Linac Reliability	8
12	Selection of ATW Demonstration System Scenario	8

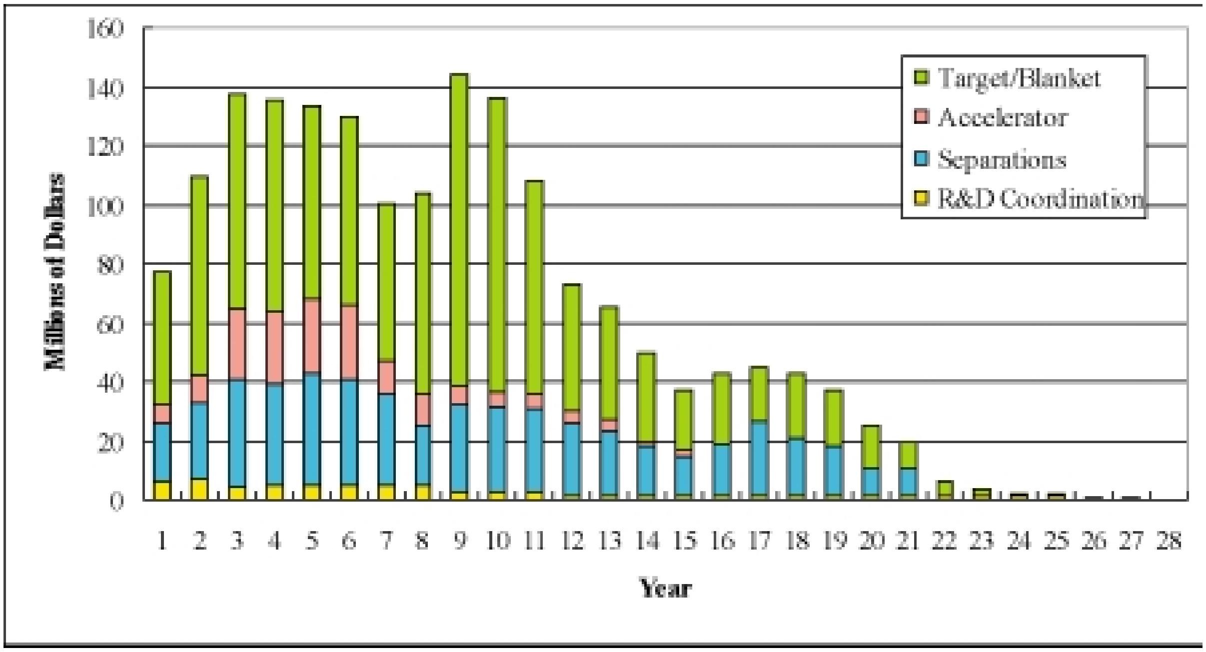

Figure A.2.2. Summary ATW R&D Costs

A.2.1. Development of Separations Technologies and Waste Forms

In an ATW system, the Separations Technologies and Waste Forms component provides three necessary functions:

1) Processes the inventory of spent fuel to extract TRU elements and the long-lived fission products technetium and iodine for the fabrication of ATW fuel and fission product target assemblies. In the processing operation, uranium, which comprises about 95% by weight of spent fuel, is purified sufficiently for disposal as low-level waste or for surface storage for future use.

2) Processes irradiated ATW fuel to extract unfissioned TRU elements and newly generated long-lived fission products for recycle to the subcritical reactor in ATW fuel and transmutation assemblies.

3) Incorporates separated fission products into durable waste forms for disposal in a geologic repository.

Consideration of the Yucca Mountain Viability Assessment prompted the Separations Technology and Waste Forms TWG to specify a set of working criteria for the chemical processing of spent fuel for partitioning and transmutation within the framework of the ATW system. First, the TWG concluded that the removal of uranium from the spent fuel should be done in such a way that the uranium could be disposed of as a non-TRU, Class C low-level waste. This will remove nearly 95% of the mass of the spent fuel from subsequent, possibly more complex, extraction steps and permit storage or disposal at a cost significantly lower than that for HLW disposal. A target of better than 99.9% recovery of the uranium in the spent fuel was established. Because of the importance of the TRU elements to nonproliferation objectives and to repository performance, a recovery target of better than 99.9% TRU was adopted. And finally, the recovery target for technetium and iodine has been estimated at greater than 95% and will be confirmed or modified as a result of R&D activities. These target values refer to overall system performance.

The three separations and waste form functions are briefly described in the following sections. Further details can be found in the Separations Technologies and Waste Forms TWG Report on the CD-ROM accompanying this report. The Separations Technologies and Waste Forms R&D roadmap is shown in Figure A.2.3.

A.2.1.1. Spent Fuel Processing

Three alternative processes were considered:

Preferred Process. The TWG recommends as the preferred separations process for development a hybrid system, consisting of an initial PUREX-based aqueous processing step that will be termed "UREX," followed by a series of pyrochemical steps collectively termed the electrometallurgical (EM) process. The UREX process would produce a pure uranium stream for disposal as waste or storage for future use, technetium and iodine streams for target or waste form fabrication, and an actinide-fission product oxide stream. The EM process would then separate the TRU elements from the fission products and convert the TRU to a metallic form suitable for fabrication of ATW fuel.

Alternative Process 1. The recommended alternative process is an "all pyro" option that uses a variation of the basic EM pyroprocess to perform all aspects of the required separations without any aqueous steps.

Alternative Process 2. A second alternative process consists of an initial UREX aqueous processing step, followed by an aqueous TRUEX-based step, and in turn followed by the EM process.

A.2.1.2. ATW Fuel Processing

The reference ATW fuel is a steel clad metallic fuel with a nominal fuel composition of 23 wt% TRU and 77 wt% zirconium. Processing of discharged ATW fuel is designed to extract the TRU elements (for recycle into fresh ATW fuel) and technetium and iodine fission products (for incorporation in ATW target or waste form assemblies) and to provide waste streams that are compatible with either the ceramic (e.g., glass-bonded sodalite) or metallic (e.g., zirconium - iron alloy) waste form. The TWG selected pyrometallurgical processes for the treatment of ATW fuel because of their robust and compact nature, ability to handle fuel cooled for only a few months, compatibility with the desired waste forms, and cost-effectiveness. Two options were considered for treating irradiated ATW fuel, a chloride volatility process (with two variants) and an electrometallurgical process. The difference between the two options is the method by which the zirconium, the major component of the fuel, is removed from the actinide and fission products.

The preferred option for ATW irradiated fuel processing is based on a chloride volatility process (similar to the Kroll process) for zirconium extraction coupled to an electrowinning process for actinide and fission product separation. Chloride volatility was chosen as the mechanism for TRU and zirconium separation because of the high zirconium content in the fuel and the existing industrial experience in zirconium metal production. The proposed electrochemical processes are similar to those used by the Integral Fast Reactor Program at Argonne National Laboratory (ANL) and for the purification of nuclear materials at Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL).

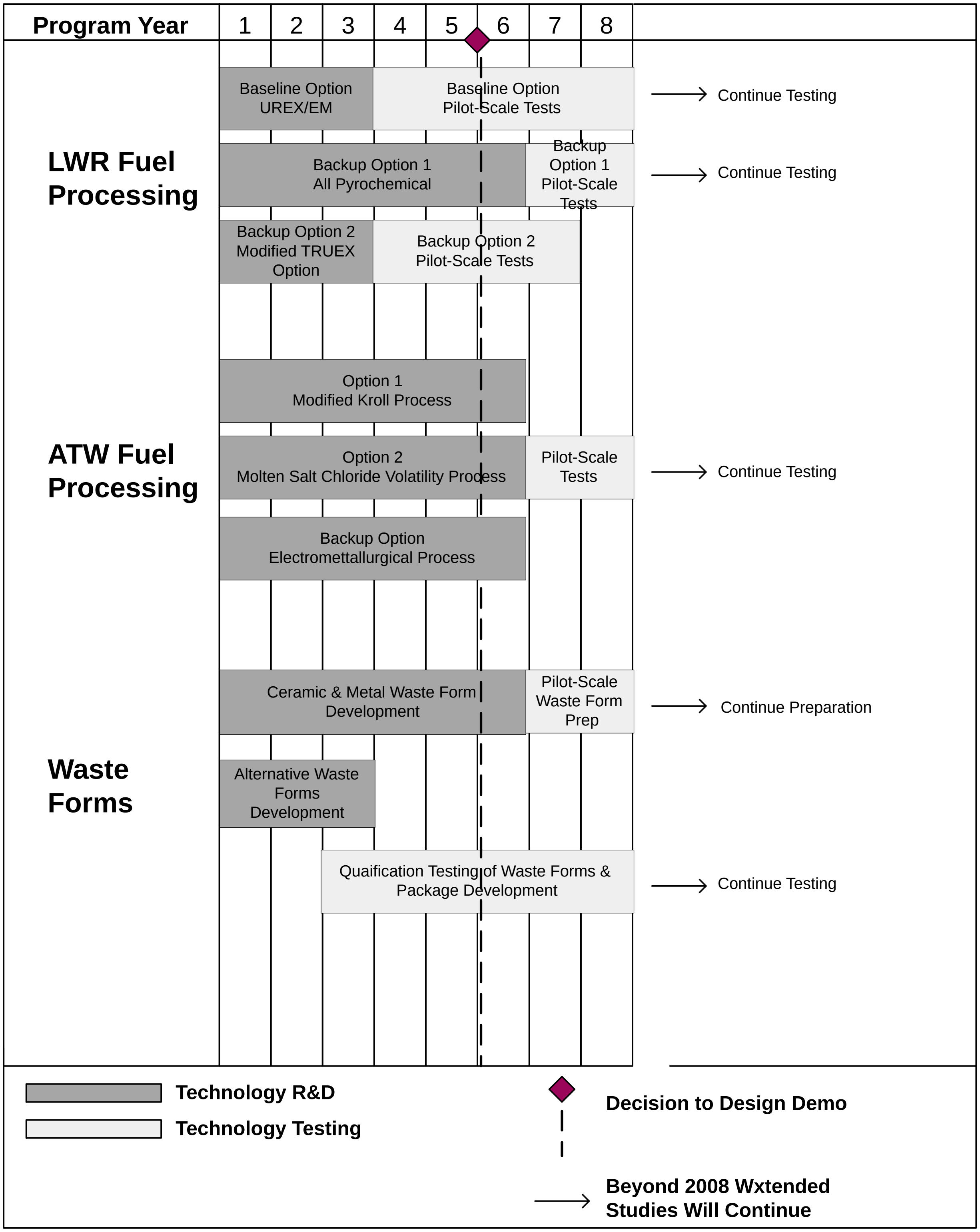

Figure A.2.3. Separations Technology and Waste Form R&D Roadmap

A variant of the classic chloride volatility technology referred to as the Molten Salt Chloride Volatility Process (MSCVP) would be investigated. The goal of the MSCVP, namely digestion of the zirconium matrix, is the same as in the classic chloride volatility process. In the MSCVP, chlorination of the zirconium matrix occurs in a molten chloride salt phase and is mediated by a less stable metal chloride such as bismuth chloride that is soluble in the molten chloride salt. The conditions used in this approach are still sufficiently oxidizing to form gaseous zirconium tetrachloride. The active metal fission products, rare earths, and TRU components of the spent fuel are also oxidized to form non-volatile metal chlorides that are soluble in the molten chloride salt. The TRU elements can then be removed from the molten salt by electrowinning.

A.2.1.3. Waste Forms

The separations technologies described in the spent fuel and ATW fuel processing sections of this report require limited development of HLW forms that are similar to waste forms being produced under the aegis of other programs. The cladding hulls from this process will constitute a HLW stream and will be fabricated into a zirconium-metal waste form. All other HLW will be carried through to the pyrochemical treatment process.

The preferred pyrochemical processes for spent fuel processing and ATW fuel-processing operations will result in two types of HLW forms. The waste streams include salt-borne and metallic materials that are to be immobilized for disposal in glass-bonded sodalite and a metal waste form alloy, respectively. The development of these waste forms is already proceeding; they are presently being qualified for the repository disposal of fission products and actinides from the treatment of the Experimental Breeder Reactor-II (EBR-II) spent nuclear fuel. Because ATW systems will destroy TRU elements and the significant long-lived fission products, ATW waste forms will contain only trace amounts of these long-lived isotopes. The demonstrated behavior of the ceramic and metal waste forms indicates that they are well suited to geologic disposal and perform as well as the borosilicate glass waste form developed for immobilization of fission products separated in aqueous processes.

A.2.1.4 Key Technical Issues

A.2.1.4.1. Spent Fuel Processing Technical Issues

The key technical issues in application of the UREX process are:

1) High recovery (99.9%) of the actinide elements.

2) Selection of a suitable plutonium reductant that does not significantly alter the composition of the actinide product stream.

3) Separation and recovery of neptunium in high yield (99.9%).

4) Separation and recovery of the long-lived fission products iodine and technetium.

5) Demonstration that a Class C low-level uranium waste can be produced at high yield (99.9%).

6) Ability to calcine the actinides in the aqueous product stream in a fashion that permits their transfer to the EM process.

The key technical issues for the TRUEX process are:

1) Demonstration of 99.9% recovery of the actinide elements

2) Separation and recovery of greater than 95% of the technetium present.

3) Identification of the optimum combination of stripping and wash reagents in order to minimize the generation of secondary waste during the TRUEX operations.

Most of the technology required for the EM steps in any spent fuel processing option has been demonstrated, at least at the laboratory scale. Thus, for the EM processes in general, the major technical challenge is scale-up of the process to support the construction of the demonstration plant. If the all-pyro alternative for spent fuel processing is chosen, two additional requirements come into effect, the requirement to produce a non-TRU uranium stream and the requirement to separate technetium from the cladding hulls. The key technical issues to meeting the target state of the EM technology are:

1) Production of a non-TRU uranium stream (all-pyro alternative only)

2) Separation of technetium from zircaloy cladding hulls (all-pyro alternative only)

3) Separation and isolation of iodine

4) Scale-up of all process steps and equipment.

A.2.1.4.2 ATW Fuel Processing Technical Issues

In general, the key technical issues for the processing of irradiated ATW fuel are much the same as those encountered in other nuclear chemical engineering environments. They include optimization of the actinide separation efficiency and recovery of selected fission products (technetium and iodine), process scale-up and parameter optimization, waste minimization, and materials compatibility and lifetime in corrosive, high-temperature, and radiation environments.

Specific technical issues associated with components of the baseline option of the ATW fuel processing include 1) spent fuel chopping/grinding system reliability at high throughput; 2) optimization of the interface between the off-gas and chloride volatility systems; 3) chemical and metallurgical behavior of technetium and the actinides in the chloride volatility system; 4) americium, curium, and technetium electrochemical behavior in the actinide electrowinning process; 5) the development of pilot- to demonstration-scale iodine separation processes; and 6) the compatibility of process residues with the desired waste forms.

The specific technical issues for the alternative option of the ATW fuel processing are 1) the adaptation of zirconium electrorefining experience to the treatment of zirconium-based nuclear fuels, which includes studies of the chemical behavior of the actinides and technetium in the process; 2) the compatibility of the process residue with currently proposed waste forms; 3) the development of waste forms capable of accepting fluoride-based molten salts; and 4) the development of pilot- to demonstration-scale iodine separation processes.

A.2.1.4.3. Waste Form Technical Issues

The key technical issues for the ceramic waste form are 1) the definition of the waste stream composition, 2) the development of full-scale processing methods, and 3) the development of waste minimization and salt recycling technology. The full-scale processing methods must be capable of processing ~75 t (~33 cubic meters) of the qualified ceramic waste forms per year for each operating ATW station.

The key technical issues for the metal waste form are 1) the definition of the waste stream composition, 2) the characterization and qualification of zirconium-8 stainless steel waste form, 3) the development of full-scale processing methods for salt removal and casting, and 4) the definition of process residuals that must go to the waste form (e.g., residual technetium, if any). The full-scale processing methods must be capable of processing ~55 MT (~7 cubic meters) of the qualified metal waste forms per year for each operating ATW station.

A.2.1.5. Research Program Cost and Schedule

The R&D costs for the separations technologies and waste forms component of ATW is roughly $500M over 21 years. This includes laboratory-scale research and pilot-scale testing up to, but not including, construction and initial operation of a full-scale demonstration facility. The costs broken out by Spent Fuel Processing, ATW Fuel Processing and Waste Form Development are shown in Figure A.2.4.

A.2.2. Development of Target/ Blanket Technology

In an ATW system, the accelerator provides a proton beam that strikes a target. The proton-target reaction product is an intense neutron flux. A blanket, composed of TRU elements and long-lived fission products recovered from spent fuel, surrounds the target. The neutrons generated in the target cause fission in the blanket of TRU and transmute the long-lived fission products by neutron absorption. Thus, the target/blanket is the "core" of the ATW system. Significant heat is produced, primarily from TRU fission in the blanket assemblies, so cooling must be provided. Target/blanket technology choices are integrally related and are affected by the choice of coolant. Technology development programs and key decision points for these inseparable subsystems are illustrated in Figure A.2.5 and discussed in the following sections.

A.2.2.1 Target Technology

Two target concepts would be evaluated: a solid tungsten target and a liquid lead bismuth eutectic (LBE) target. A target decision affects coolant alternatives.

A.2.2.1.1. Liquid Lead Bismuth Eutectic Target

In this preferred concept, a proton beam is sent into a subcritical core cooled by liquid LBE. The source neutrons are produced by spallation directly on the LBE primary coolant. A window cooled by the same LBE primary coolant provides the separation between the accelerator (beam guide) and the subcritical blanket. The source neutrons multiply in the surrounding blanket, which is composed of a hexagonal array of metallic fuel element bundles. Fission heat generated in the blanket is removed by the LBE-forced circulation through

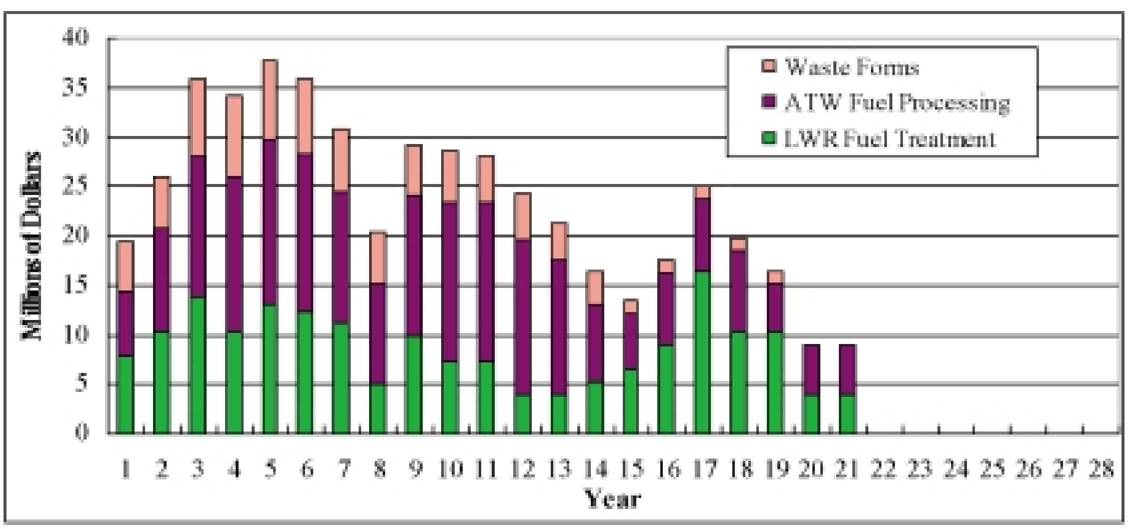

Figure A.2.4. Separations Technologies and Waste Forms R&D Costs

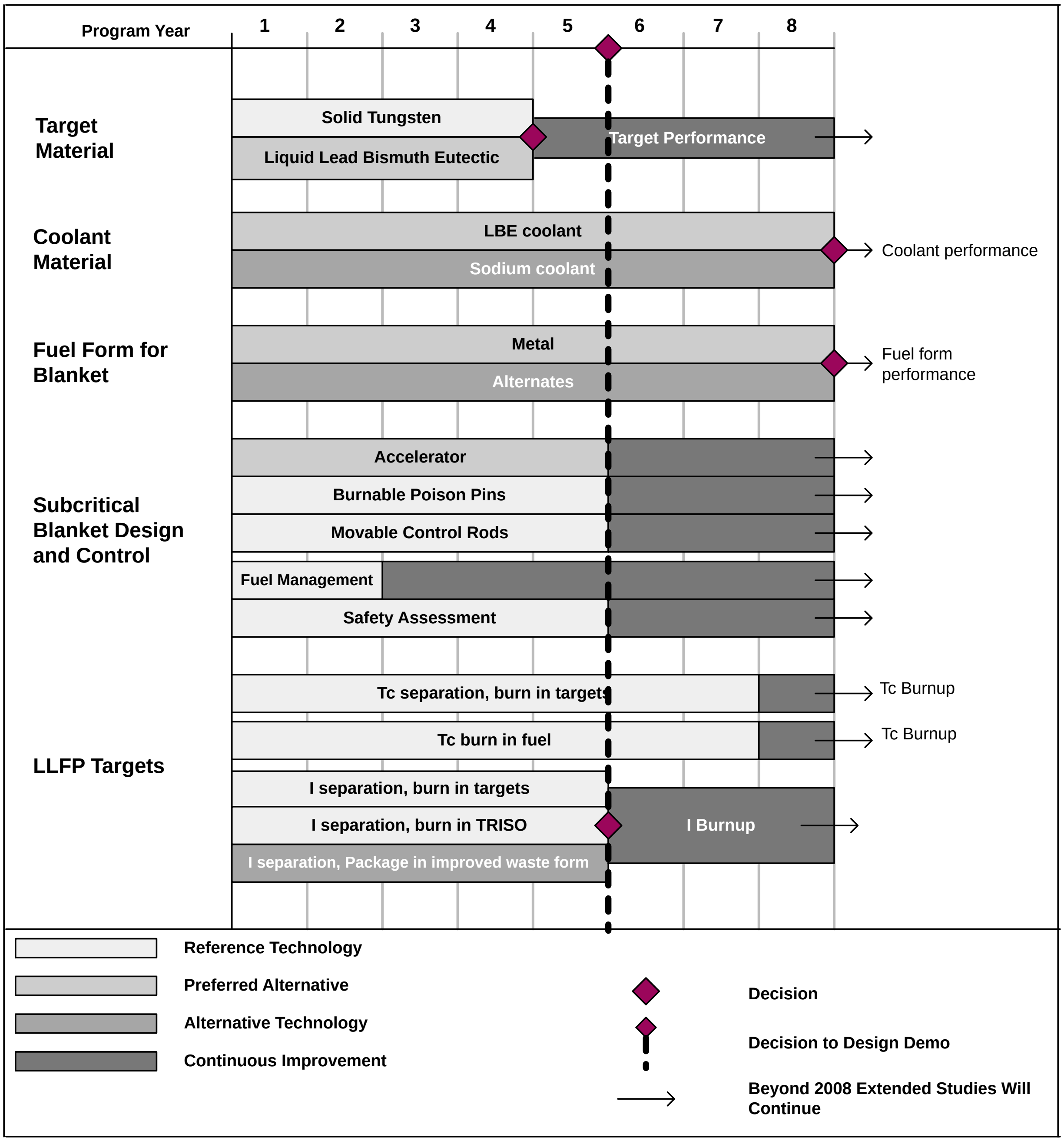

Figure A.2.5. Target/Blanket Technology R&D Roadmap intermediate heat exchangers into a secondary LBE loop and from there into a steam generator.

LBE (the eutectic composition is 44.5 wt% lead, 55.5 wt% bismuth) possesses some unique physico-chemical properties making it an excellent coolant and target. Its low melting point (123.5°C), high boiling point (1670°C), and very low vapor pressure allow for a wide operating temperature range, make coolant boiling very unlikely, and enhance coolant loop safety. The high density of LBE combined with wide permissible temperature range offers natural convection cooling capability for enhanced passive safety. LBE's low chemical activity eliminates energetic chemical reactions with air and water.

LBE has a very high useful neutron production from spallation (as many as 30 neutrons per GeV proton) and extremely low neutron capture cross section. The integration of nuclear coolant, spallation target, and reflector using the same fluid in the ATW LBE target concept drastically simplifies the blanket design by streamlining flow configuration and removing target and reflector structures.

A.2.2.1.2. Solid Tungsten Target

In this alternative, a proton beam is directed into a tungsten target cooled by molten sodium or helium gas. A window cooled by the same primary coolant provides the separation between the accelerator (beam guide) and the blanket. The core consists of a hexagonal array of metallic fuel element bundles. Fission heat generated in the blanket is removed by the forced circulation of the coolant through intermediate heat exchangers into a secondary loop and from there into a conventional steam generator.

The U.S. has extensive experience in the development of sodium-cooled fast reactor systems and helium cooled, high-temperature gas reactor (HTGR) systems. Much of that technology development is directly transferable to ATW. To apply sodium reactor or HTGR technology to ATW, additional development activities should include the design and testing of a sodium or helium-cooled solid target and determining the effects of spallation products on chemistry control and corrosion.

A.2.2.2 Blanket Technology

A metal-matrix metallic fuel, a TRU-10 wt% zirconium fuel particle dispersed in a zirconium matrix is chosen as the reference blanket fuel form, with the TRU-zirconium fuel particle volume fraction adjusted to provide a bulk fuel composition of zirconium-25 wt% TRU. A low-temperature fabrication process appears to be desirable to enable the retention of TRU elements in the fuel form. It is believed that processes currently in development for fabrication of low-enrichment research and test reactor fuel, e.g., powder metallurgy, can be successfully employed.

An alternative means of fuel fabrication would be carried in case some characteristics of the preferred fuel choice or its fabrication prevent deployment. The alternative method consists of injection casting of long metallic slugs in a manner similar to that employed at ANL for EBR-II fuel since the 1960s, intended more recently for Integral Fast Reactor (IFR) fuel. This fuel would have the disadvantage of being not as thermal-shock resistant as dispersion fuel and would require processing at temperatures that are expected to volatilize significant amounts of americium and perhaps some other TRU elements.

Transmutation of long-lived fission products such as technetium-99 and iodine-129 is also a goal. Technetium may be separated from spent fuel and fashioned into transmutation targets for placement around the blanket circumference. Even if not intentionally separated, the ATW recycle process will carry much of the technetium into new ATW fuel, where it will be transmuted. Because of its volatility, iodine will not be carried forward in the ATW fuel cycle and is difficult to quantitatively collect and form into transmutation target assemblies. Issues on iodine targets and transmutation would be addressed in R&D activities.

A.2.2.3. Nuclear Design and Safety

The fertile-free fuel composition proposed for use in ATW maximizes the net destruction rate of TRU elements per unit of thermal power but leads to a high rate of reactivity loss with burnup. If unmitigated, this reactivity loss would result in a decline of the power output and a loss of electricity production revenue. The loss can be compensated through active reactivity control (e.g., control rods) or active source control (requiring an accelerator sized for the minimum system reactivity). Analyses to date have assumed from three to six 100-day irradiation intervals (and up to six shuffling zones in the blanket). The equilibrium cycle discharge burnup is approximately 30% with the six-cycle residence time.

The objective of minimizing proton energy loss as the beam is introduced into the target/blanket region drives the design toward thin barriers (called "windows"). This conflicts with traditional containment strategies that rely on thick barriers to mitigate severe accidents. The design solution will likely differ from traditional containment strategies and may require careful safety evaluations.

Some of the issues to be resolved by nuclear design and safety R&D include:

- Design for degree of subcriticality.
- Accommodation of burnup reactivity loss.
- Accommodation of feed composition variation with recycle.
- Long-lived technetium and iodine isotope transmutation strategy.
- Determination of dynamic behavior.
- Safety strategy and analysis.
- Validation of simulation tools.

Efforts to address these issues will begin with system trade studies, blanket design and fuel management studies for ATW concept options, and establishment of validated simulation tools. Initially, general safety issues will be addressed; as blanket design efforts begin for specific ATW Demonstration Plant and Prototype Plant configurations, analyses of specific accident scenarios will be performed.

A.2.2.4 Coolant and Ancillary Systems Technology

Early problems with LBE nuclear systems (corrosion of structural materials, oxygen balance, and handling of the polonium generated through neutron irradiation) have reportedly been solved in the course of developing LBE systems for submarine propulsion reactors in Russia. The Russians deployed this technology in their nuclear submarine reactors and have accumulated over 80 reactor-years of experience (mostly in 150-MWt units). Even with successful technology transfer, significant development issues remain including factors of scale, the impact of spallation product contamination of the coolant, and materials exposure to proton irradiation, which will be introduced by the U.S. ATW program.

It is assumed because sodium components have been successfully built and operated at varying scale at several different sodium-cooled reactors in the U.S., that the technology is sufficiently mature for implementation in an ATW demonstration plant.

If a fast-spectrum gas-cooled target and blanket system were chosen, it would use metallic fuel of the type considered for the liquid metal alternative. Thus, the process for separating uranium and fission products from the uranium and actinides, and the process for forming fuel rods would be the same for both systems.

For the ATW program, all three coolants would be carried in the R&D program until sufficient data are collected to support a decision for system demonstration.

A.2.2.5 Research and Development Program Cost and Schedule

The target/blanket R&D roadmap was developed based on the current status of technology development, and the activities deemed necessary to reach a reasonable feasibility decision for demonstration are shown in Figure A.2.5.

Target/blanket R&D activity costs are based on estimates of similar activities planned for the Advanced Liquid Metal Reactor (ALMR) program. Large component development costs are based on actual costs for similar activities performed for the Clinch River Breeder development program at ANL. Historical cost data have been escalated to calendar year 1999 dollars (Figure A.2.6).

Total R&D costs for the target/blanket portion of ATW are about $1,030M. The added cost of LBE development is plotted separately.

A.2.3 Development of Accelerator Technology

The accelerator proposed for ATW is in the same class as the accelerator designed for the Accelerator Production of Tritium (APT) project. Thus, the design has benefited from an extensive RD&D program and has reached a high level of technical maturity and credibility. The supporting RD&D program is still underway and will be completed, in terms of the major risk-reduction elements, by the fourth year. Completion of the Low Energy Demonstration Accelerator (LEDA) program will mark a major technological milestone and add considerably to the technology level of assurance. Continuation of the LEDA program utilizing the facility as a test bed for ATW reliability development and testing will maintain this level of assurance. The normal-conducting copper accelerating structure technology is well understood, and the APT RD&D program for the high-energy part of the linac will bring the superconducting accelerating-structure technology up to a comfortable level. The ATW accelerator component development and testing program is laid out in the Figure A.2.7. This roadmap emphasizes the development and testing of accelerator subsystems. A major issue for the R&D program is accelerator reliability, in terms of reducing the frequency of beam interrupts to a level appropriate for driving a power-producing subcritical assembly.

A.2.3.1. Accomplishments of the APT Accelerator R&D Program

Given that the APT accelerator RD&D program completes the program planned for the present project funding profile through the fourth year, it will have demonstrated, through LEDA activities, a complete high-power proton linac front-end up to 8 MeV, including:

- Operation of a 6.7-MeV 350-MHz rfq (radio frequency quadrupole), the first accelerating structure in the low-energy part of a high-power proton linac, operating at 100 mA with 100% duty factor.
- Operation of a short section (8 MeV) of a 700-MHz coupled-cavity drift tube linac, the second accelerating structure, at 100 mA, with 100% duty factor.
- Confirmation of the match between these two accelerating structures.
- Benchmarking of beam-dynamics codes used in high-power linac design, and confirmation of beam halo production to assess the beam-loss threat in the high-energy linac.
- Operation of 1-MW level rf power sources and power distribution systems at 350 MHz and 700 MHz.

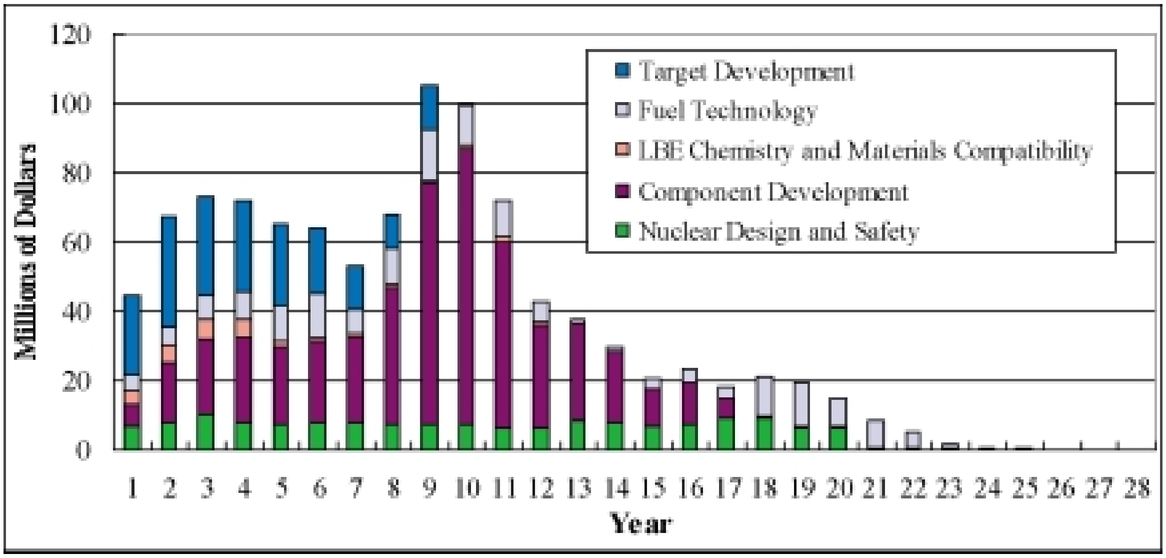

Figure A.2.6. Annual Target/Blanket R&D Costs

- Beam diagnostics for measuring high-power beam properties at low energies.
- Integrated accelerator system operation, control, and fault recovery schemes.

It will also have demonstrated a complete medium velocity superconducting rf-cavity cryomodule, including:

- Performance of five-cell superconducting cavities
- Performance of high-power rf couplers at 200 to 250 kW
- Cryogenic thermal performance of an integrated high-energy linac superconducting rf accelerating unit at full power.

These two sets of activities, LEDA and the cryomodule prototyping, form the basis for the ATW R&D effort.

A.2.3.2 The Deployment-Driven ATW Accelerator

The reference accelerator design for an ATW station consists of two 1.0-GeV, 45-mA continuous wave proton accelerators driving eight transmutation assemblies (Figure A.2.8.). The first ATW accelerator facility needed to drive a demonstration test transmutation assembly will be a single accelerator designed to generate a 45-MW beam of protons but installed only with components necessary to meet beam current requirements for driving a single prototype transmuter at 840 MWt (about 12 mA). Later, additions of rf power systems would upgrade the accelerator for the full-scale demonstration of up to four 840-MWt transmuters.

A.2.3.3 ATW Accelerator R&D Issues

The key issues to be addressed by the ATW Accelerator program would be to:

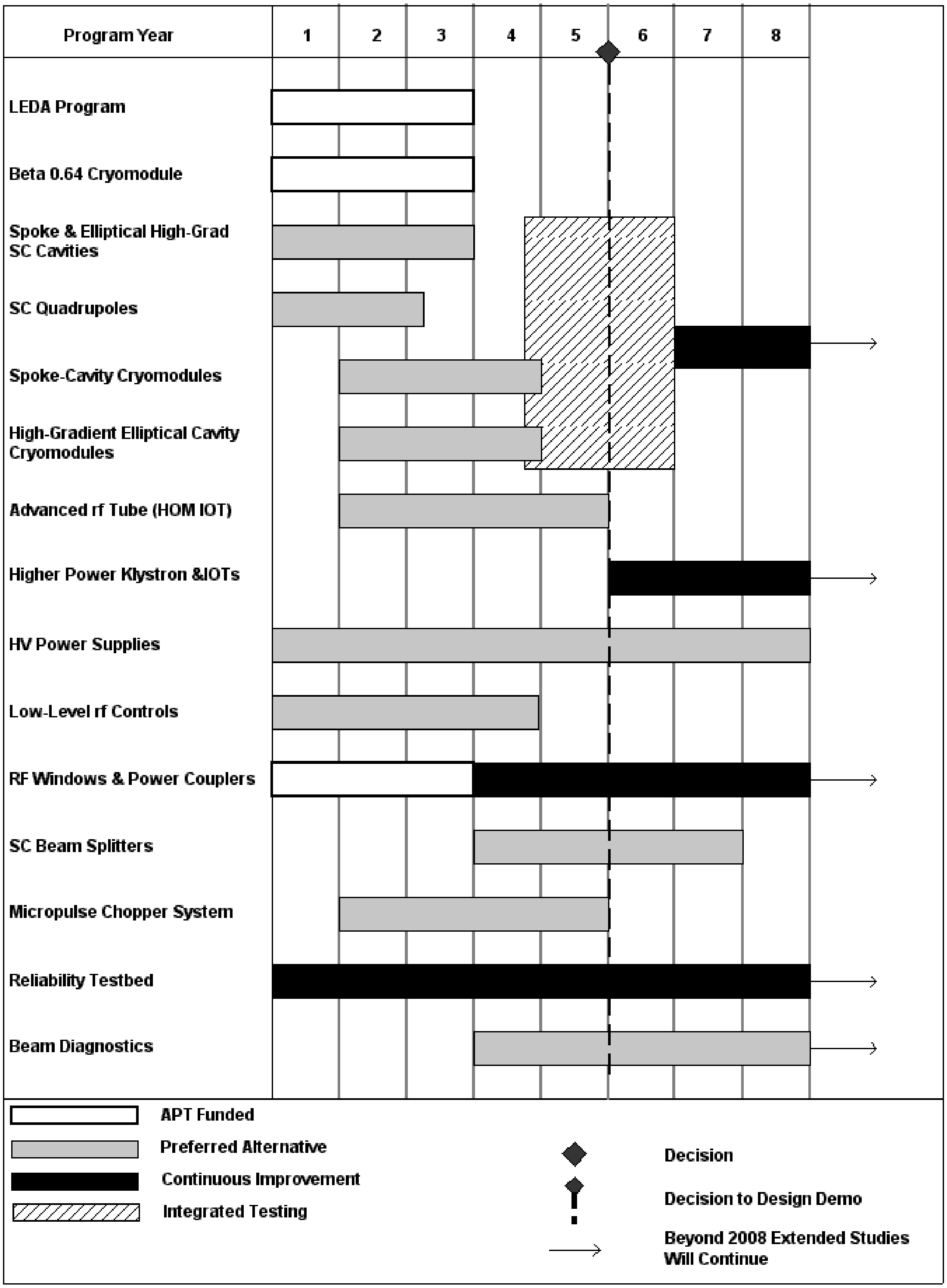

Figure A.2.7. Roadmap of R&D Activities Necessary for the Development of an ATW Accelerator

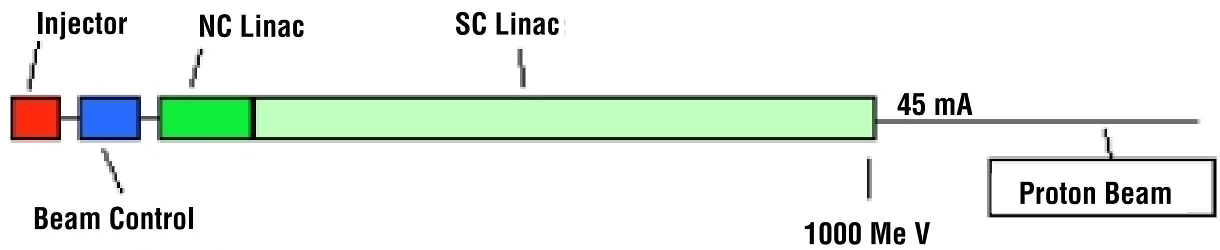

Figure A.2.8. Deployment-Driven ATW Accelerator Concept

- Achieve high accelerator reliability, both for consistent electrical power to the grid and to reduce thermal transients in the transmutation assembly.
- Develop and test beam-sharing systems needed for a single linac serving multiple targets.
- Develop and test high-beta cryomodules containing high-gradient cavities.
- Develop and test lower-beta superconducting accelerating structures.
- Improve the power efficiency of rf systems and components.
- Develop and test low-energy beam control devices.
- Develop and test long-lifetime rf windows.
- Develop and test modernized rf power components: couplers, high voltage power supplies, and isolation valves.

A.2.3.4 ATW Accelerator R&D Roadmap

Considering the status of current activities on related high-power accelerator programs and the issues that need to be addressed to meet the requirements of the ATW accelerator, the R&D roadmap was developed (Figure A.2.7). The timeline is the first through eighth year of the program, with the main accelerator R&D work completed in the eighth year. The first column on the roadmap lists the main components to be developed and tested. The first six activities address issues concerned with accelerator cavity development. The next five activities address issues concerned with rf component development and enhancement. The next two activities address issues concerned with beam control. Additional activities address issues concerned with reliability of major components and beam diagnostics.

A.2.3.4.1 Description of R&D Roadmap Activities

The five groups of accelerator R&D activities in Figure A.2.7 are further described in this section. Descriptions of activities funded under the APT Program are not provided here.

Activities relating to Superconducting Accelerator Development are the following:

- High-gradient, elliptical superconducting cavities: Extend the development and testing of medium-beta and high-beta superconducting cavities to substantially higher accelerating gradients than in APT (> 10MV/m).
- Spoke-type high-gradient superconducting cavities: Extend the development and testing of new

high-gradient accelerating cavities using spoke-type (1/2 wave) resonators. This would allow a shorter accelerator and larger bore radii; relaxing alignment, steering, and matching tolerances; and reduce beam loss and activation.

- Superconducting quadrupoles: Design and testing of quadrupole magnets for medium and high-beta cryomodules. The design will build on designs developed for a earlier accelerator.
- Spoke-cavity cryomodules: Build and test a low-beta prototype cryomodule containing spoke-type cavities and quadrupoles; demonstrate building block of the lowest-energy part of a superconducting accelerator.
- High-gradient elliptical cavity cryomodules: Build and test a medium-beta and high-beta prototype cryomodule containing high-gradient elliptical cavities and quadrupoles; demonstrate building blocks of the medium-energy and high-energy parts of a superconducting accelerator.

Activities relating to rf component development and enhancement are:

- Advanced rf tube (high-order mode inductive output tube [IOT]): Build and test improved version of high-power high-order mode IOTs as rf generator alternative to klystrons.
- Higher-power klystrons: Design, build, and test prototype klystrons that would operate at up to 2.4 MW of power in continuous wave mode. Commercially available klystrons operate at a maximum of 1 MW of continuous wave power.
- High voltage power supplies, circulators, loads, etc.: Design, build, and test high voltage power supplies using isolated gate bipolar transistors (IGBT). High-power ferrite and high-power resistive circulators are being built by industry to function at 1 MW of power levels.
- rf windows and power couplers: R&D would focus on life-time testing and demonstration of long-term reliability of these rf system components.

Activities relating to beam control are:

- Super-conducting rf beam splitters: Design, build, and test a prototype beam splitter consisting of superconducting elliptical cavities excited with deflecting (transverse) magnetic fields followed by an appropriate magnetic septum and transporter magnetic system.
- Micro-pulse chopper system: Design, build, and test a prototype proton-beam chopper system for the front-end of the ATW accelerator. These choppers will allow inhibiting beams to individual transmuters during maintenance and refueling.

Activities relating to accelerator reliability are:

- rf power station/cavity reliability test bed: Build and operate a test facility to identify and evaluate rf power station interruption and/or failure characteristics as a basis for improvement of rf system reliability. This activity would be followed-up by redesign and testing of rf components having improved performance and reliability.
- Injector reliability test stand: Build and operate a test facility to identify and evaluate injector beam interruption and/or failure characteristics as a basis for injector reliability improvement. This activity would be followed-up by redesign and testing of the injectors for improved performance and reliability.
- Component reliability tests on demonstration linac: Design and operate a testing program for the demonstration accelerator to identify and evaluate reliability (interruption and/or failure mechanisms) characteristics (e.g., type, frequency, measurement, symptoms, and impacts) as a basis for improvement of component reliability, and the follow-up redesign and testing of demonstration accelerator components for performance and reliability.

Activities relating to beam diagnostics are:

- Beam diagnostic components: Design and testing of reliable components that measure the physical characteristics of the high-energy, high-current proton beam throughout the accelerator, including position, current, energy, density profile, emittance, and energy spread. Some devices exist and will be tested for appropriate and reliable use. Others need R&D since this will be a first-of-a-kind accelerator.

A.2.3.5 Estimated Costs of the ATW Accelerator Program

The annual distribution of the accelerator R&D costs is shown in Figure A.2.9. The total costs for accelerator R&D would be $165M including long-term reliability testing.

A.3. Integrated ATW Demonstration Program

After about five years of R&D and testing of major components of ATW technology, sufficient information and confidence will have been developed to provide a basis for designing a demonstration accelerator/transmutation facility (ATF) and a spent fuel/ATW fuel processing, fuel/target fabrication, and waste management facility (fuel and target facility [FTF]). Title II (detailed) design would begin in the sixth year. Conceptual and preliminary design of these facilities will have begun by the third year and be developed with the R&D. R&D, particularly for FTF components, will continue in existing facilities at several U.S. government sites or international collaborative sites while design and construction of the ATF and FTF proceed. This demonstration facility could be constructed and operated in the U.S. or at an international collaborative site. The accelerator would be the first component built to conduct long-term testing and develop reliability. All major equipment and components of the demonstration facility would be at full "station" specifications. However, the demonstration program would proceed in steps, operating the components at increasing capacities until all station components are at full operation.

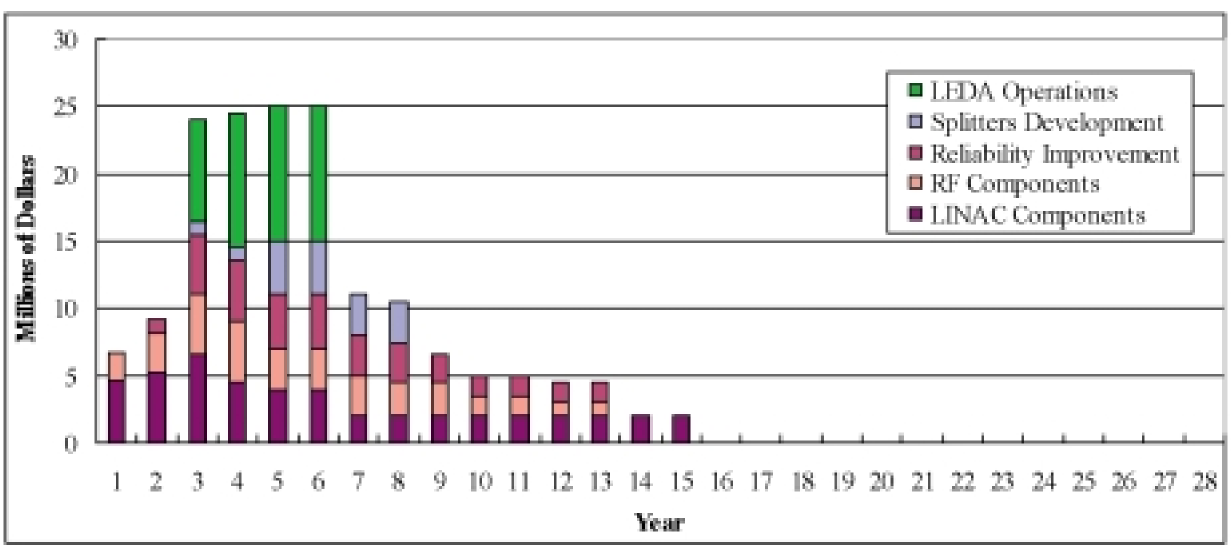

Figure A.2.9. Cost Profile for ATW Accelerator R&D

A.3.1. Integrated Technology Demonstration Program

The integrated technology demonstration is planned to bring together the major components of the ATW system at a single site in project-designed facilities to fully demonstrate the:

- Reliability, controllability, and efficiency of the accelerator beam.
- Efficiency and effectiveness of the spallation target and transmuter core operations.
- Effectiveness of transmutation of TRU in ATW fuel assemblies.
- Effectiveness of transmutation of technetiun and iodine.
- Effectiveness of spent fuel and ATW fuel processing and fabrication.
- Effectiveness of waste management.
- Reliability of electricity generation.

The first major facility to be constructed would be the ATF, and the first component to be constructed would be the accelerator. The accelerator is not only more advanced in design but needs to run longer to develop reliability. The other major ATF component would be the spallation target and transmuter. The initial fuel for the transmuter would be supplied from existing facilities used during R&D. The ATF would initiate operations using a 12-mA beam of 1.0 GeV protons (1/4 full power but full energy) on a transmuter target designed to produce 30 MWt. This configuration, shown in Figure A.3.1, would start operation in the fifteenth year and run for four years to acquire data and operational experience. The heat generated would be discharged to the environment through heat exchangers. In the nineteenth year, the configuration of the transmuter would be upgraded to produce 420 MWt. This configuration would be operated for about two years to confirm operations and system performance. At this time, the performance of the technology would be reviewed and a decision made to move to the next level of demonstration.

In the twenty-second year, the system would be shut down to upgrade the accelerator to its full capacity of 45 MW of power. Three heat exchangers would be provided to dump 3/4 of the beam power. The transmuter would be upgraded to its full capacity of 840 MWt. A steam generator would be added to convert the transmutation energy to steam (full system size), and a 620 MWe turbine generator would be added to convert the steam to 310 MWe (1/2 system size). The fuel for this configuration would be supplied by the newly constructed full-sized FTF, which would be running at near capacity. This demonstration system would

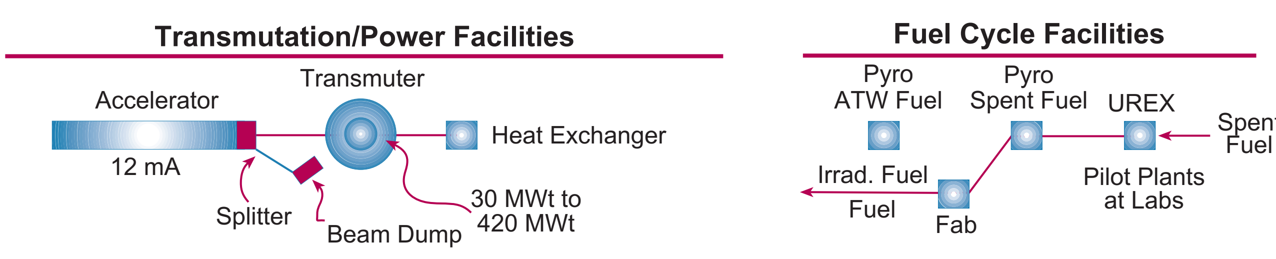

Figure A.3.1. Initial ATW Demonstration Configuration start up in the twenty-fourth year and would operate about three years. The configuration is shown in Figure A.3.2. At this time, the performance of the technology would be reviewed and a decision made to move to the next level of demonstration.

In the twenty-seventh year, a second 840-MWt transmuter and a second full-capacity steam generator (for the second transmuter) would be added, and the capacity of the turbine generator would increase to full power (620 MWe). The FTF would supply the fuel for the two-transmuter power block, which would begin operations in the twenty-eighth year and operate in the demonstration mode for about one year before going into the production mode. The configuration is shown in Figure A.3.3. At the end of the twenty-eighth year, the performance of the technology would be reviewed and a decision made to move to the next level of demonstration.

The demonstration operation would be completed by the end of the twenty-eighth year. All major components of the ATW technology system will have been demonstrated at full design capacity. Any further expansion of the facility at this site, U.S. or international, would constitute deployment and is addressed in Section A.5, Life-Cycle Costs for ATW Technology.

A.3.2 Integrated Demonstration Program Schedule

The key milestones of the ATW integrated demonstration can be expressed as the dates when fuel loading occurs during the phased operations, as summarized in Table A.3.1.

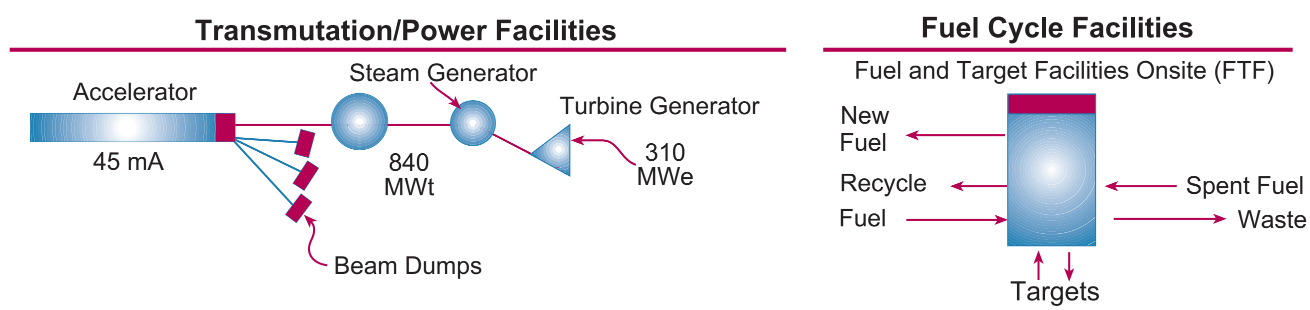

Figure A.3.2. Second ATW Demonstration Configuration

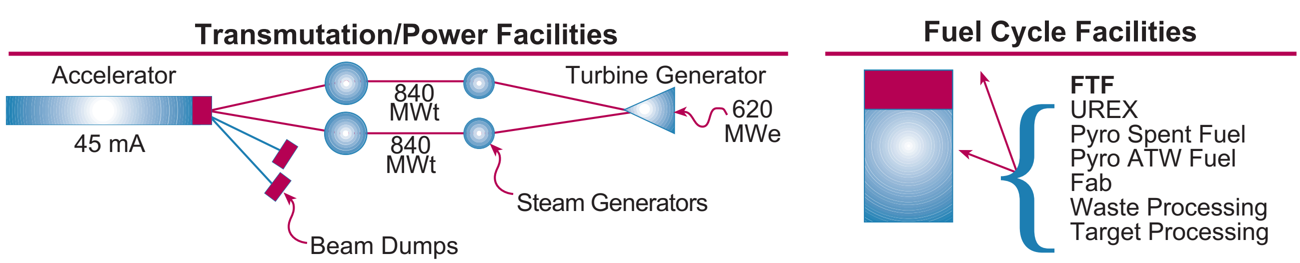

Figure A.3.3. Third ATW Demonstration Configuration

A time line showing the dates of design and construction steps of the two major facilities (ATF and FTF) and the start and operation times of the demonstration runs are shown in Figure A.3.4. Before each fueling, the performance of the technology would be reviewed and a decision made to move to the next level of demonstration.

A.3.3. Integrated ATW Demonstration Program Costs

Demonstration program costs start in about the third year with programmatic (systems engineering; planning; management; environment, safety, and health; quality, and organizational) and conceptual and preliminary design activities. The demonstration program begins to accelerate in the sixth year with the decision to initiate detailed designs. In the twenty-eighth year, the demonstration program completes its objectives. The costs over that period are provided in an annual profile in Figure A.3.5.

The total costs for ATW technology demonstration is expected to be about $9.4B, in addition to the $1.8B for R&D, or about $11.2B for ATW technology RD&D through the twenty-eighth year.

Table A.3.1. Summary of Fuel Loading Milestones

Item	Description	Start Date
1	Initial Demonstration Configuration—30 MWt	Year 15
2	Second Demonstration Configuration—420 MWt	Year 19
3	Third Demonstration Configuration—840 MWt and 310 MWe	Year 24
4	Fourth Demonstration Configuration—840 MWt and 620 MWe	Year 27

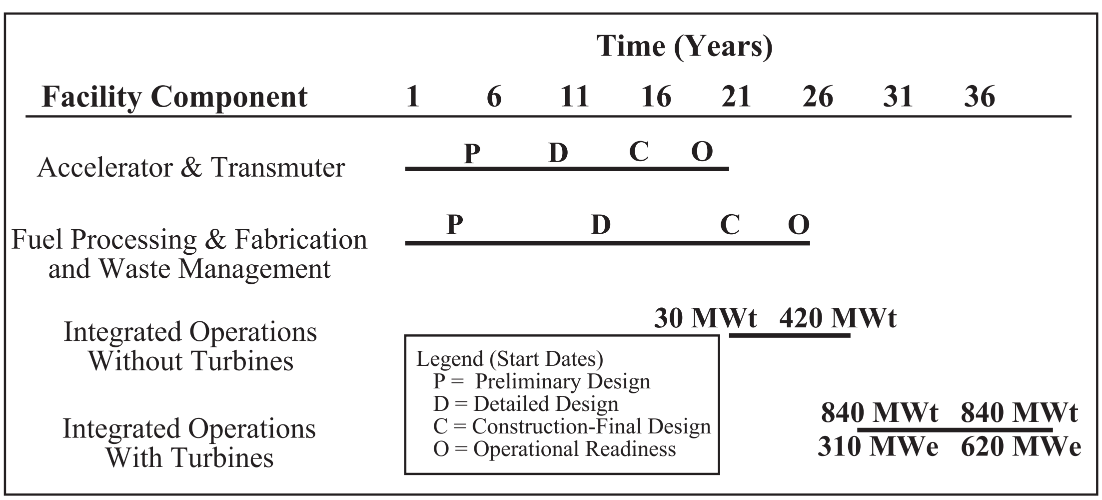

Figure A.3.4. Summary Time Line for ATW Demonstration Facilities

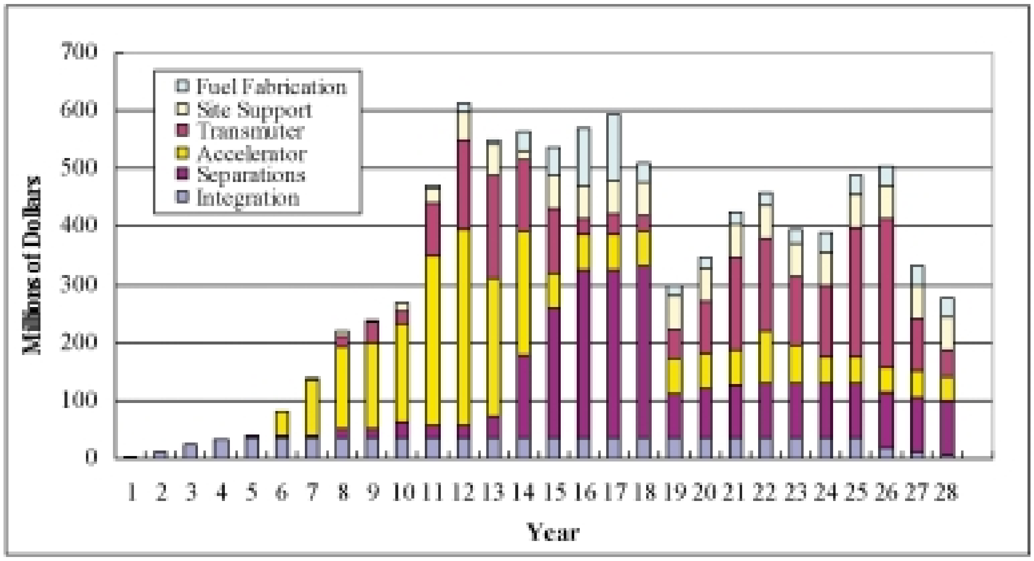

Figure A.3.5. ATW Technology Annual Demonstration Costs

A.4. Integrated Schedule for Developing ATW Technology

Preparation of the ATW technology development schedule included consideration of ongoing development efforts in related projects. Technical issues as well as programmatic, environmental, regulatory, and institutional issues were considered. Key elements included in these considerations are:

- Preparing for and conducting programmatic, technical, design, construction, and operations decisions required by DOE and other government agencies.
- Planning and conducting environmental and safety reviews.
- Planning and management of the organization, R&D, testing, demonstration, design, construction, and operation of the project.
- Strategies for planning, and conduct of licensing (assumed to be Nuclear Regulatory Commission [NRC]) and permit (local, state, and federal) documentation and reviews.
- Strategy to apply for a NRC Standard Plant Certification during the demonstration period to facilitate the deployment of additional plants and stations as early as possible.
- Government site selection and operational readiness reviews and approval processes.
- Timely consideration of public interests and involvement.
- Phasing of fuel processing and target manufacturing at laboratory and government sites.
- Inclusion of critical components in demonstration phases to completely demonstrate all system components as soon as reasonable.
- Strategy to expedite resolution of institutional issues during the demonstration period.
- Use of incentives to expedite privatization/deployment planning during the demonstration period.

ATW technology R&D and demonstration development schedule risks have been addressed and minimized during this roadmapping effort by using related information from other more mature programs and appropriate scheduling of above issues early in the

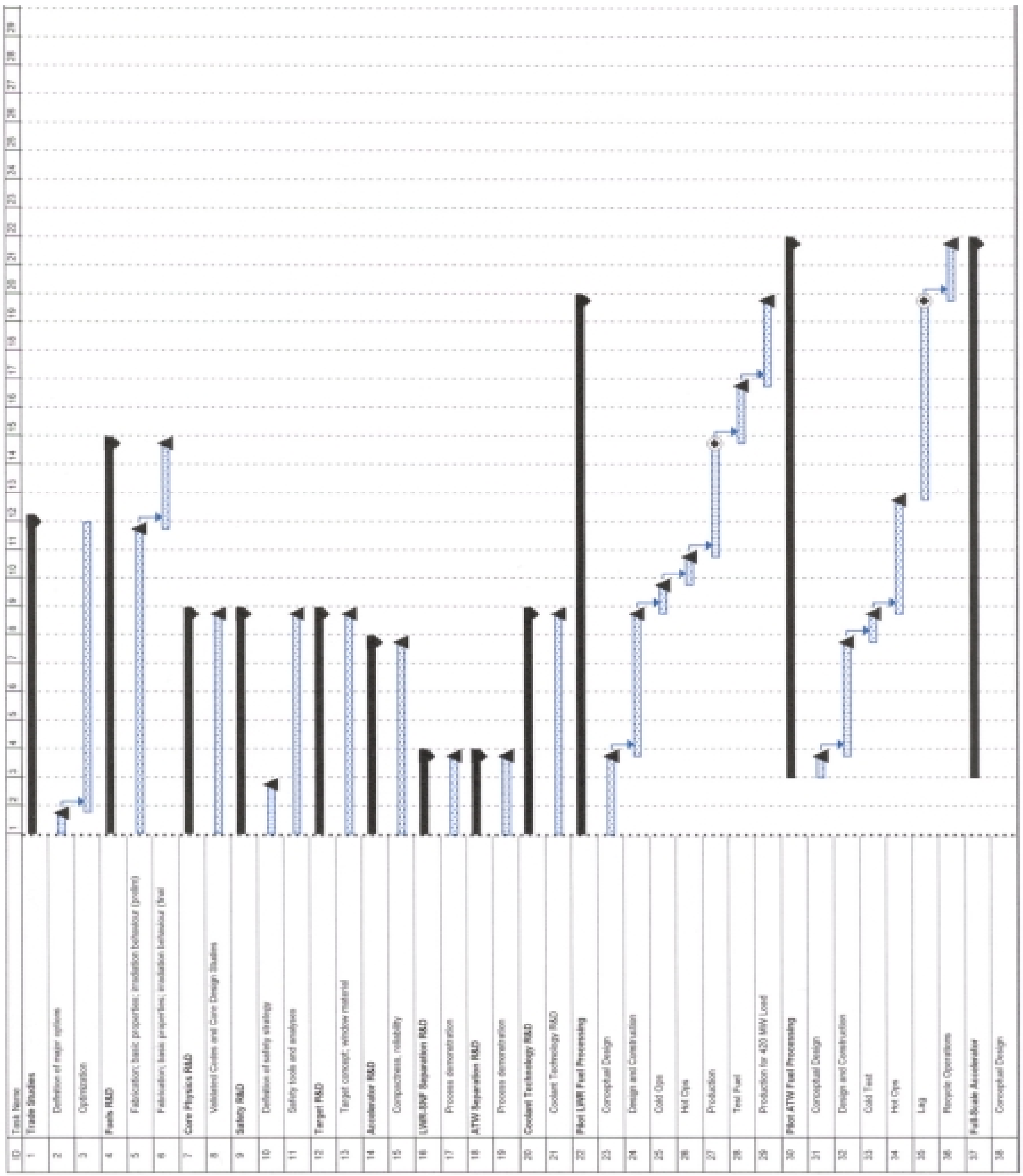

Figure A.4.1. RD&D Schedule by Cost Element

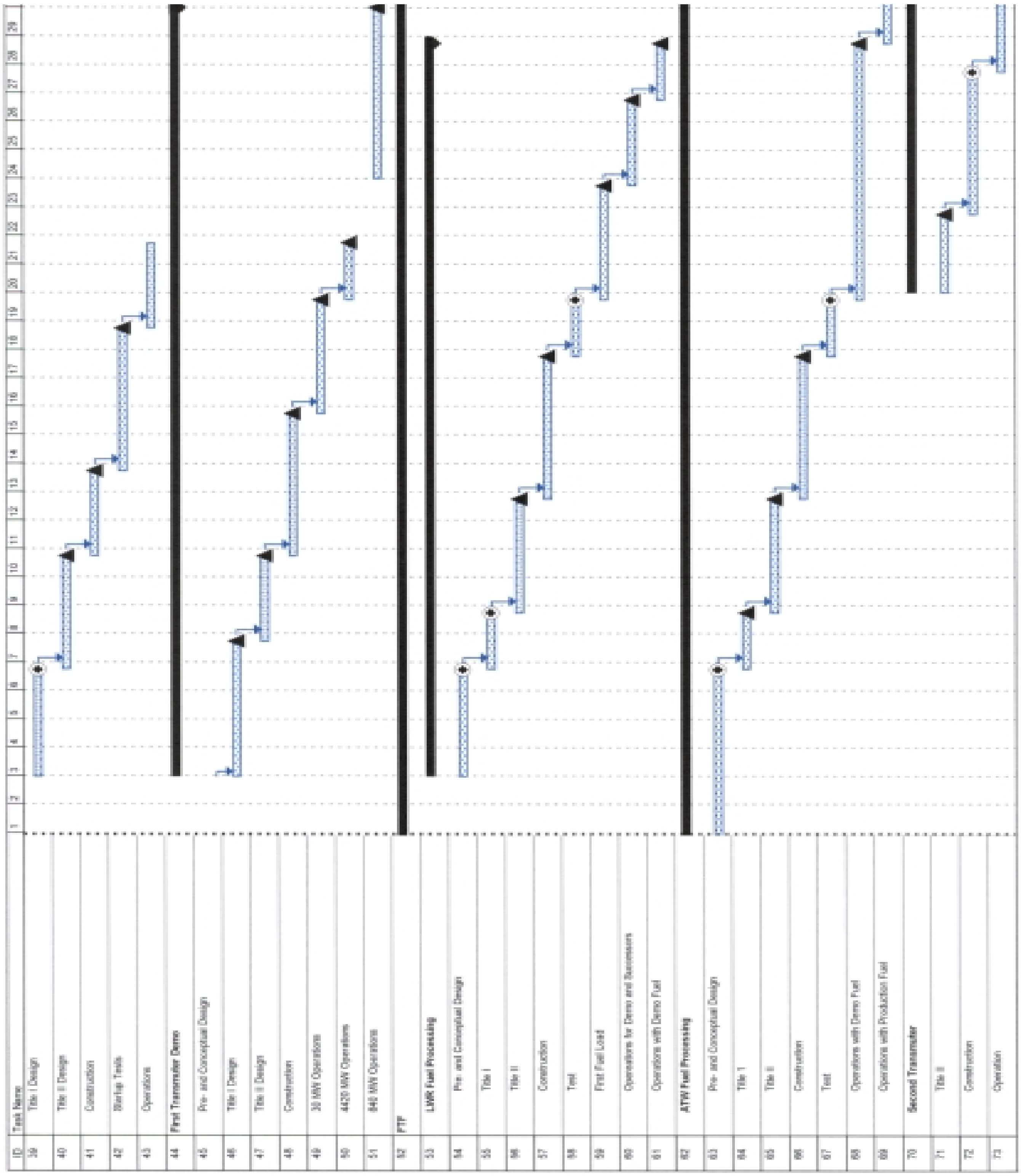

Figure A.4.1. (Continued) RD&D Schedule by Cost Element

RD&D phases of the ATW project. The results of these considerations are expressed in Figure A.4.1.

A.5. Life-Cycle Costs for ATW Technology

Life-cycle cost information is presented in Section 7.0 of this report. Details of the life-cycle cost developed are presented in the full report, *Estimated Cost of an ATW System,* included on the attached CD-ROM.

Glossary

Accelerator A device such as a linac, cyclotron or synchrotron that accelerates charged particles or nuclei to high energies with electric fields.

Actinides The 14 elements following actinium that form the actinide series in the Periodic Table of the Elements.

β (beta) Term used in accelerators to express particle velocity as a function of the speed of light (= v/c).

Background radiation Radiation from natural radioactivity always present in the environment, including cosmic rays and radiation from naturally radioactive elements.

Blanket The fuel and transmutation assemblies that make up the subcritical system surrounding the central target area of a transmuter.

Cross section The apparent cross-sectional area of a target nucleus for a given reaction with neutrons or to accelerated charged particles (e.g., protons).

Dose rate A quantity of radiation absorbed by an individual, usually measured in rem/yr or sv/yr.

Energy Amplifier The objectives of the Energy Amplifier concept are to burn actinides and produce power through a thorium fuel cycle. The concept originated in CERN in cooperation between Italy, Spain, and France, and has now expanded to other European countries.

Fissile Capable of undergoing nuclear fission induced by thermal or fast neutrons.

High-level radioactive waste Waste resulting from the processing of highly radioactive material such as spent fuel.

Iodine-129 A radioactive isotope of iodine having a half-life of 16 million years. It is a relatively low abundance fission product.

Isotope One of two or more atoms having the same atomic number but different numbers of neutrons. Examples are uranium-235 and uranium-238, which are both isotopes of uranium.

k_{eff} The neutron multiplication factor of a reactor system. Values greater than or equal to 1 describe a critical system, whereas values less than 1 describe a subcritical system.

LBE Lead bismuth eutectic, proposed liquid metal coolant for the ATW transmuters.

linac A linear accelerator, distinguished from circular machines like cyclotrons, betatrons, or synchrotrons. Radio frequency (rf) linacs (the majority of linacs) get their energy to accelerate particles from rf power.

MOX Mixed oxide fuel containing plutonium instead of uranium-235 enriched uranium as the main fissile component.

Nuclear reactor A device containing fissionable material in which a nuclear chain reaction is initiated and self-sustained with inherent or extended control, with the resulting heat typically used for generating electric power.

Proliferation The spread of fissile nuclear materials to other countries for potential use in weapons production.

Processing The separation of fuel discharged from a reactor into potentially useful products and waste.

Radionuclide A radioactive isotope.

Reactor core An assemblage of fuel rods, control rods, and other elements that make up the core of a critical reactor.

Spallation reaction When a particle with ultra-high energy strikes a nucleus it will likely collide with one or more nucleons and then escape with part of its original kinetic energy. By means of this scattering process, one or a few nucleons may get a large fraction of the energy of the incident particle. The latter nucleon or group of nucleons may be ejected from the nucleus without further collision, or they may share their energy with a few other nucleons. In most collisions with ultra-high energy particles, the target nuclei are excited to energies far greater than the binding energies of individual nucleons. Nucleons or groups of nucleons escape until the residual nucleus is left in a relatively stable state. At energies of 100 MeV or more, a dozen or more nucleons may escape, and many combinations of protons and neutrons have been observed. Reactions of this kind are described by the term spallation.

Spent fuel Fuel that has been withdrawn from a nuclear reactor following irradiation.

Subcritical reactor A nuclear reactor (see definition above) in which the chain reaction can be sustained only by introducing additional neutrons by means of an external drive such as a particle accelerator.

Target A heavy metal (solid or liquid) with which high-energy protons interact to produce neutrons by spallation.

Technetium-99 A radioactive isotope of technetium with a half-life of 210,000 years. It is a relatively abundant long-lived fission product.

t Metric ton (or tonne), a unit of mass in the metric system equal to 1,000 kilograms.

Tonne A unit of mass in the metric system equal to 1,000 kilograms or approximately 2204.62 pound mass. Also known as metric ton (t).

Transmutation Transformation of one isotope element into another by one or a series of nuclear reactions.

Transmuter A subcritical reactor that uses transuranic elements (TRU) as fissile material and is driven by accelerator-produced neutrons.

Transuranic elements alpha-emitting radionuclides that are heavier than uranium, with half-lives greater than 20 years.

Transuranic waste Waste materials (excluding high-level waste and certain other waste types) contaminated with alpha-emitting radionuclides that are heavier than uranium, with half-lives greater than 20 years and occur in concentrations greater than 100 nanocuries per gram.

Acronyms and Abbreviations

ADS	Accelerator-driven systems
ADTT	Accelerator-driven transmutation technologies
ALMR	Advanced liquid metal reactor
ANL	Argonne National Laboratory
APT	Accelerator production of tritium
ASME	American Society of Mechanical Engineers
ATF	Accelerator/target facility
ATW	Accelerator transmutation of waste
BNL	Brookhaven National Laboratory
CD-ROM	Compact disk, read-only memory
CEA	Commissariat a l'Energie Atomique (French Atomic Energy Commission)
CERN	Conseil Europeen pour la Recherche Nucleaire (European Organization for Nuclear Research)
D&D	Development and demonstration
dc	Direct current
DES	Duke Engineering & Services
DP	U.S. Department of Energy, Office of Defense Programs
DOE	U.S. Department of Energy
DOE-RW	U.S. Department of Energy, Office of Civilian Radioactive Waste Management
EBR-II	Experimental Breeder Reactor II
EIS	Environmental Impact Statement
EM	Electrometallurgical process
ENEA	Ente per le Nuove Technologie, l'Energia e l'Ambiente (Italian National Agency for New Technology, Energy and Environment)
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EU	European Union
FFTF	Fast Flux Test Facility
FP	Fission product
FTF	Fuel and target facility
GeV	Giga-electron volt
HLW	High-level radioactive waste
HTGR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IFR	Integral fast reactor
INEEL	Idaho National Engineering and Environmental Laboratory
IOT	Inductive output tube
IPPE	Institute of Physics and Power Engineering
ISTC	International Science and Technology Center
JAERI	Japan Atomic Energy Research Institute
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBE	Lead bismuth eutectic

LEDA	Low-energy demonstration accelerator
LLFP	Long-lived fission products
LLNL	Lawrence Livermore National Laboratory
LLW	Low-level waste
LMR	Liquid-metal reactor
LWR	Light-water reactor
mA	milli-Ampere
MINATOM	Russian Atomic Energy Ministry
MIT	Massachusetts Institute of Technology
MOX	Mixed oxide (fuel)
MSCVP	Molten salt chloride volatility process
MTU	Metric tons of uranium
MWe	Megawatt electric, a unit of electrical power
MWt	Megawatt-thermal, a unit of thermal power
NC	Normal conducting
NE	U.S. Department of Energy, Office of Nuclear Energy, Science and Technology
NAS	National Academy of Sciences
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NERI	Nuclear Energy Research Initiative
NRC	Nuclear Regulatory Commission or National Research Council
NWPA	Nuclear Waste Policy Act of 1982
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PUREX	(PLutonium URanium EXtraction) Commonly used process based on using tributylphosphate for fuel reprocessing
pyro	Pyrometallurgical processing
R&D	Research and development
RD&D	Research, development, and demonstration
rf	Radio frequency
rfq	Radio frequency quadrupole
RW	U.S. Department of Energy, Office of Civilian Radioactive Waste Management
SLAC	Stanford Linear Accelerator Center
SF	Spent fuel from power reactors
SNL	Sandia National Laboratories
SNS	Spallation neutron source
SSIG	System Scenario and Integration Group
STATS	Separations technology and transmutation systems
TRU	Transuranic elements
TRUEX	TRansUranic EXtraction
TWG	Technical Working Group
UREX	(URanium EXtraction) An aqueous process for processing spent fuel
WIPP	Waste Isolation Pilot Plant
WSRC	Westinghouse Savannah River Company

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