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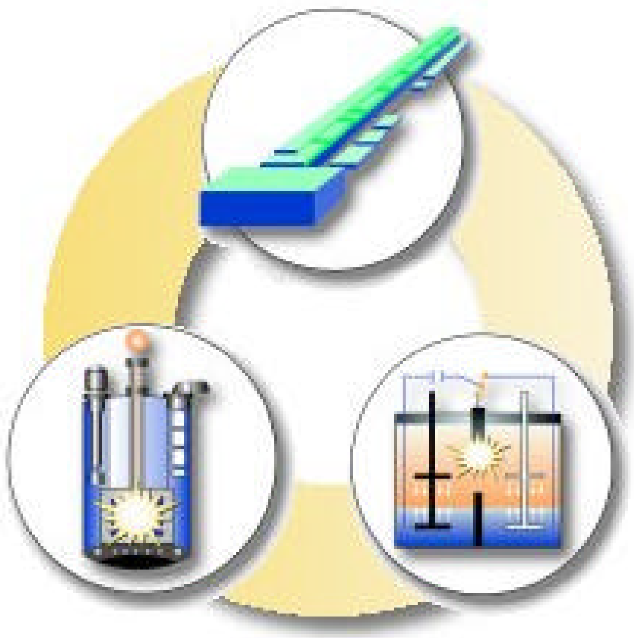

A Roadmap for Developing ATW Technology:

System Scenarios & Integration

September 1999

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ROADMAP FOR THE DEVELOPMENT OF ACCELERATOR TRANSMUTATION OF WASTE: SYSTEMS SCENARIOS

REPORT OF THE ATW ROADMAP SYSTEMS SCENARIOS AND INTEGRATION TECHNICAL WORKING GROUP

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ACRONYMS/ABBREVIATIONS

ABR	Actinide Burning Reactor
ADS	Accelerator Driven System
ADTT	Accelerator-Driven Transmutation Technologies
AGR	Advanced Gas-Cooled Reactor
AGS	Alternating Gradient Synchrotron at BNL
ALMR	Advanced Liquid Metal Reactor
ANL	Argonne National Laboratory
APT	Accelerator Production of Tritium
ATR	Advanced Test Reactor
ATW	Accelerator Transmutation of Waste
AMFM	Alternative Means of Financing and Managing
BESSY	Berliner Elektronenspeicherring-Gesellschaft fur Synchrotronstrahlung (Synchrotron radiation facility in Berlin)
BISO	BI (two) layer Silicon carbide coated Oxycarbide (a particle fuel type for the high temperature gas cooled reactor)
BNL	Brookhaven National Laboratory
BOR-60	BOR-60 (Russian 60 MW Fast Reactor)
BWR	Boiling Water Reactor
CANDU	Canadian Heavy Water Moderated Reactor
CEG	Contact Expert Group
CERMET	Ceramic-Metal fuel
CFR	Code of Federal Regulations
DEMO	Demonstration Facility for ATW
DTU	Denatured Thorium-Uranium fuel
EBR-II	Experimental Breeder Reactor II
ED&D	Engineering Development & Demonstration
EIA	Energy Information Agency
EIS	Environmental Impact Statement
EM	Electrometallurgical
EU	European Union
Fermi	Physicist who led team to create first sustained critical nuclear reaction
FFAG	Fixed-Fluid Alternating Gradient
FFTF	Fast Flux Test Facility
FOAK	First Of A Kind
FP(f.p.)	Fission Product
FR	Fast Reactor
FTF	Fuel and Target Facility
HLW	High Level Waste
HTGR	High Temperature Gas Cooled Reactor
HVDC	High Voltage Direct Current
IAEA	International Atomic Energy Agency

ACRONYMS/ABBREVIATIONS
(Contd.)

IK	Infiltrated Kernel
INEEL	Idaho National Engineering & Environmental Laboratory
IPPE	Institute of Physics & Power Engineering
ISIS	Institute of Systems, Informatics and Safety (located at the Rutherford Appleton Laboratory)
ISTC	International Science and Technology Center
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBE	Lead-Bismuth Eutectic
LE	Life Extension
LEDA	Low Energy Demonstration Accelerator
LLFP	Long-Lived Fission Products
LLNL	Lawrence Livermore National Laboratory
LMFBR	Liquid Metal Fast Breeder Reactor
LMR	Liquid Metal Reactor
LWR	Light Water Reactor
M&O	Management & Operating (Contractor)
MA (M.A.)	Minor Actinides
MINATOM	Ministry for Atomic Energy of the Russian Federation
MOX	Mixed Oxide
MTIHM	Metric Tonnes Initial Heavy Metal
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NOAK	Next Of A Kind
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
OCRWM	Office of Civilian Radioactive Waste Management
OECD	Office for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
OTA	Office of Technology Assessment (no longer functional)
P&T	Partitioning & Transportation
PBR	Pebble Bed Reactor
PMA	Plutonium and Minor Actinides
PNNL	Pacific Northwest National Laboratory
PRISM	Power Reactor Innovative Small Module
PWR	Pressurized Water Reactor
QA	Quality Assurance
RD&D	Research, Development & Demonstration
RF (rf)	Radio Frequency
S&T	Separations & Transportation
SC	Superconducting

ACRONYMS/ABBREVIATIONS
(Contd.)

SINQ	Swiss Institute Neutron Source at Paul Scherrer Institute in Switzerland
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratory
SNS	Spallation Neutron Source
SNT	Special Nuclear Technology
STATS	Separations Technology and Transmutation Systems
STF	Spallation Test Facility
TRISO	TRI (three) layer Silicon carbide coated Oxycarbide (a particle fuel Type for the high temperature gas cooled reactor)
TRU	Transuranic
TRUEX	Transuranic Extraction
TVA	Tennessee Valley Authority
TWG	Technical Working Group
UREX	Uranium Extraction
USDOE (DOE)	U.S. Department of Energy
WIPP	Waste Isolation Pilot Plant
WSRC	Westinghouse Savannah River Corporation

EXECUTIVE SUMMARY

As requested by the U.S. Congress, a roadmap has been established for development of ATW Technology. The roadmap defines a reference system along with preferred technologies which require further development to reduce technical risk, associated deployment scenarios, and a detailed plan of necessary R&D to support implementation of this technology. Also, the potential for international collaboration is discussed which has the potential to reduce the cost of the program. In addition, institutional issues are described that must be addressed in order to successfully pursue this technology, and the benefits resulting from full implementation are discussed.

This report uses as its reference a fast spectrum liquid metal cooled system. Although Lead-Bismuth Eutectic is the preferred option, sodium coolant is chosen as the reference (backup) technology because it represents the lowest technical risk and an excellent basis for estimating the life cycle cost of the systems exists in the work carried out under DOE's ALMR (PRISM) program. Metal fuel and associated pyrochemical treatment is assumed. Similarly a linear accelerator has been adopted as the reference.

A reference ATW plant was established to ensure consistent discussion of technical and life cycle cost issues. Over 60 years of operation, the reference ATW plant would process about 10,000 tn of spent nuclear reactor fuel. This is in comparison to the current inventory of about 40,000 tn of spent fuel and the projected inventory of about 86,000 tn of spent fuel if all currently licensed nuclear power plants run until their license expire. The reference ATW plant was used together with an assumed scenario of no new nuclear plant orders in the U.S. to generate the deployment scenario for ATW.

In the R&D roadmap, key technical issues are identified and timescales proposed for the resolution of these issues. For the accelerator the main issue is the achievement of the necessary reliability in operation. To avoid frequent thermal transients and maintain grid stability the accelerator must reach levels of performance never previously required. For the target material the main technical choice is between solid or liquid targets. This issue is interlocked with the choice of coolant. Lead-Bismuth eutectic is potentially a superior choice for both these missions but represents a path with greater technical risk. For the blanket metal fuel has been selected.

The reference method of processing of spent fuel from LWRs to provide the input material for ATW is chosen to be aqueous because of the large quantity of uranium that needs to be brought to a state that it can be treated as Class C waste. Again this is the path of least technical risk although the pyrometallurgical option will be pursued as an alternative. Processing of the fuel after irradiation in ATW will be undertaken using pyrometallurgical methods. The transmutation of Tc and I represents a special research issue and various options will be pursued to achieve these goals.

Finally the system as a whole will need optimization from a reactivity and power control perspective. Varying accelerator power is feasible but can lead to overdesign of the accelerator; other options are movable control rods, burnable poison rods, and adaptations of the fuel management strategy.

A key recommendation is that, in the first year of any ATW program, trade studies intended to lead to confirmation of technology choices and optimization of design be conducted. These studies will then be used to define future R&D. A science-based approach to the necessary R&D is recommended to establish the performance capabilities of key technologies such as Lead-Bismuth Eutectic (LBE), acquire necessary materials properties, nuclear and thermal-hydraulic data and to validate tools such as simulation codes that will be used to optimize and establish the safety envelope for ATW. International collaboration will be important in this endeavor.

There are institutional issues which might provide barriers to development and implementation of ATW. These issues include the ability of the federal government to provide the necessary resources to carry out an ATW program, public acceptance of both policy and siting of facilities and the regulatory requirements for ATW. These challenges are likely to be less demanding during research and development phase of any ATW project.

Other countries and international groups are pursuing Accelerator-Driven Transmutation Technologies. There are clear synergies between any program in the U.S. and these programs, and many opportunities for technology partnerships that will reduce cost. These partnerships should be pursued as an integral part of the program. Three specific proposals for the form the collaboration might take are developed.

An ATW research program will keep the U.S. in contact with developments in nuclear technology world-wide and help to preserve U.S. leadership in nuclear issues. The direct benefits of ATW technology could include improved repository performance (reduction in radionuclide inventory, elimination of criticality concerns and customized waste forms) and the energy production from spent fuel.

1.0 INTRODUCTION

1.1 Background

Congress appropriated $4 million in fiscal year 1999 for the Department of Energy (DOE) to conduct a study of accelerator transmutation of waste (ATW) technology. DOE, in coordination with its laboratories. Was requested *"…to establish a road map for the development of ATW technology that identifies: technical issues that must be resolved; a proposed time schedule and program to resolve those issues; and the estimated cost of such a program. The road map should consider and propose collaborative efforts with other countries developing ATW technology and other programs developing accelerator technology. Institutional challenges of the proposed program should be assessed as well as areas of ATW technology development that could have benefits to other ongoing programs. In addition, the road map and report to Congress should assess the potential impact of this technology on the civilian spent nuclear fuel program and the estimated capital and operational life cycle costs to treat civilian spent nuclear fuel."*

A Doe steering committee managed the overall road mapping process and assisted in the selection of participants. The major share of information in the road map was provided from three sources:

- the open literature
- a World's Expert panel that provided information on the status of international ATW developments and identified research areas with potential for collaboration, and
- four technical working groups that developed plans for specific research and development programs and addressed potentially significant institutional challenges, i.e., Systems Scenarios and Integration Technical Working Group, Target/Blanket Technical Working Group, Accelerator Technical Working Group and, Separations and Waste Forms Technical Working Group.

In addition to the technical working groups, two other studies were commissioned, one on life cycle cost and the other to assess the potential impact on the repository.

The Systems Scenarios and Integration Technical Working Group, as the name implies, was responsible for both evaluating the role of ATW in energy and waste reduction scenarios and the work of the other three technical working groups to ensure consistency of technical assumptions, schedules, and key system parameters. In response to the Congressional mandate, this report contains a technology development roadmap, identifies the technical issues to be resolved and a plan and schedule to carry out the program. This report also addresses possible international collaborations and the identification of key institutional issues as part of the system study.

This report consists of ten sections. Section 2.0 provides a brief discussion of the rationale for transmutation. Section 3.0 of this report describes technical options that might be pursued to meet the ATW mission.

The Congressional mandate identifies the need for an ATW technology road map and the development of specific R&D plans to support this road map. With this chapter, the steering committee directed the technical teams to address a specific version of ATW technology. This ATW technology is based on the use of liquid metal coolants, fast neutrons and pyrochemistry for the separations as discussed in Section 4.0 This choice is based upon some convergence in ideas among international groups but is not universally agreed on as the only technical option. Section 5.0 describes possible future scenarios for nuclear energy in the USA, and the consequences on spent fuel production. The key assumptions are highlighted and one particular scenario “no new orders”, is selected as the basis for this study. The choice of scenario was made for expediency in preparing the roadmap. No statement is made as to the likelihood or desirability of such a scenario. (ATW systems sized based upon this scenario are equally applicable in a future where there is continuing use of LWRs). While the first few sections discuss the integration of the ATW R&D planning, the implications thereof in terms of costs and benefits, institutional issues that must be addressed as well as opportunities for international collaboration.

This report should not be considered as a comprehensive evaluation of the merits of ATW technology or as recommending a particular choice of technology. Many assumptions had to be made upon energy scenarios and technology options. What this report does seek to do, in conjunction with the reports of the other working groups, is to answer the following questions:

- What technology options exist for the ATW?
- What are the necessary steps required to develop and implement the specific version of ATW technology currently identified?
- What is the R&D required, in the next 5 years, to confirm these choices and provide a basis for the development of the ATW concept?
- What institutional issues might hamper development and deployment of ATW technology in the USA?
- How could the U.S. utilize international cooperation to meet its goals?

2.0 RATIONALE FOR TRANSMUTATION

In this section, we discuss the basic rationale that underlies the consideration of transmutation as a technology to condition spent nuclear fuel before disposal of the transmutation productions in a geologic repository. In the U.S., which operates on a once-through fuel cycle, spent nuclear fuel is treated as waste. First, we need to address the question of why conditioning of spent fuel might be desirable. Second, the phenomenon of transmutation is discussed.

2.1 Reasons for Conditioning Spent Nuclear Fuel Before Disposal

The final disposition of spent fuel has been and continues to be an issue of national and international importance. In the U.S., an aggressive program is ongoing to characterize a candidate site at Yucca Mountain, Nevada for a geological repository for spent fuel and high-level waste. The Yucca Mountain repository is being sized to safely dispose of 63,000 tn[1] of spent fuel from nuclear power reactors and 7,000 tn of spent fuel and high-level waste from DOE operations. Current reactor operations in the U.S. discharge about 2000 tin of spent fuel annually.

Nuclear power reactors in the U.S. currently operate on a once-through fuel cycle. After spending a certain time in a reactor, the fresh fuel (which is comprised primarily of uranium) becomes spent fuel and is removed from the reactor. Spent fuel is normally quantified in terms of the mass of initial heavy metal (i.e., uranium) in fresh fuel. During reactor operation some of the uranium is fissioned, thus producing fission products, and some of the uranium absorbs neutrons resulting in the generation of transuranic elements. Energy release results in an insignificant loss of total mass. Spent fuel is removed from these reactors when its reactivity has decreased due to consumption of Uranium-235 (the isotope of uranium primarily responsible for fission in the reactor); the buildup of fission and activation products; and because the mechanical integrity of the fuel is reduced. Thus, spent fuel is not “spent” in the sense that all its energy has been completely used up. A typical composition of fresh and spent fuel is shown in Table 2-1.

A the time of its removal 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. These short-lived fission products can be readily retained in repositories for reasonable periods to minimize their threat to the human environment. The major constituent, uranium, can be separated and reused in fresh reactor fuel, or disposed of as low-level radioactive waste.

[1] Throughout this document we use the SI notation where tn represents 1 metric tonne.

Component	Fresh Fuel	Spent Fuel
U-238+	967.9	943.7
U-235	32.1	6.7
Plutonium		9.3
Minor actinides		1.6
Sr-90		0.4
Cs-137		0.9
Tc-99		0.9
I-129+		0.3
Other Fission Products		36.3
Total	1000.0	1000.0

\+ Includes other isotopes

This composition is for 37.2 MWt-d/kg burnup[2], 20 years after discharge (grams per kilogram of initial uranium). This composition is not the same as the average composition of spent fuel from a wide distribution of burnups with the same average burnup, (see Appendix A for discussion of computational method).

Table 2-1. Typical composition of spent fuel

In addition to the uranium and short-lived fission products, spent fuel contains relatively small quantities of plutonium, other transuranic elements, and long-lived fission products. These long-lived constituents, though small in quantity, present challenges to the performance of a repository because it is difficult to predict its performance hundreds of thousands of years in the future. The treatment of spent fuel to deal with these constituents (i.e., separation and transmutation to more benign forms) could simplify some of the technical difficulties of geologic repository disposal. Such treatment can be considered as a technology option to enhance future repository development efforts.

By removing and transmuting the plutonium, other transuranic constituents, and the long-lived fission products from spent fuel, several objectives can be met:

- Public acceptance could be improved by reducing the inventory of long-lived radionuclides in the repository thereby decreasing the period of time that the repository has to maintain integrity.
- The potential for future removal of plutonium from the repository for use in nuclear weapons is avoided.
- The energy content of the transuranics could instead be exploited in power reactors. The transuranics alone have the energy content equivalent to 25 to 30% of the energy released during the formation of the spent fuel. In additional, the remaining uranium has a very large residual energy content one to two orders of magnitude higher than

[2] Burnup is described in terms of MWt-d/kg (identical to GWt/d/tn) where MWt is the thermal power in megawatts, d is days and kg is kilograms.

the energy released. These significant energy resources can be utilized in appropriately designed power stations.

Thus the conditioning of spent fuel to remove and transmute the plutonium, other transuranics, and long-lived fission products has the potential to provide significant benefits to the overall repository disposal program, and enhance flexibility in future efforts to optimize radioactive material management.

By removing the problematic constituents in spent fuel, the repository program can achieve greater flexibility in managing the disposal of spent fuel; new options for enhanced waste-form characteristics may be fostered; the technical provability of repository performance may be facilitated; flexibility for future nuclear fuel cycles may be retained, and the siting and design of future repositories may be facilitated as a result of reduced threat from long-term migration of certain isotopes. These benefits are discussed in detain in Section 8.0.

2.2 Definition of Transmutation

The term "transmutation" can be defined as the transformation of a material into a new material by changing its nuclear structure. In the context of conditioning the constituents of spent fuel, the objective of transmutation is the conversion of problematic constituents into materials that have more favorable characteristics.

One of the most effective methods to achieve nuclear transmutation is through exposure of material to neutrons. 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 critical nuclear reactor (i.e., a system designed to maintain a steady level of neutrons in a self-sustaining configuration) or in an accelerator-driven transmuter.

In the latter, additional neutrons result from an accelerator beam of high-energy particles, e.g. protons, that collide with a dense, high-atomic-number target. 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 transformation and destruction through a variety of nuclear processes.

2.3 Accelerator-Driven Systems

The subject of this report is Accelerator Transmutation of Waste (ATW). Similar accelerator-driven transmutation systems are being studied in many countries. These systems are generally referred to as Accelerator-Driven Systems (ADS), or Accelerator-Driven Transmutation Technologies (ADTT), and encompass several technology options. Some of these options are described in Section 3.0, more detail on the international programs is given in Section 9.0

3.0 TECHNOLOGY OPTIONS FOR ATW

3.1 Introduction

The ATW components are 1) a accelerator that can deliver a proton beam with megawatts of beam power, 2) a target/blanket (also known as a transmuter) 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 isolate long-lived radioactive isotopes and minor actinides for initial or recycle irradiation (see Fig. 3-1).

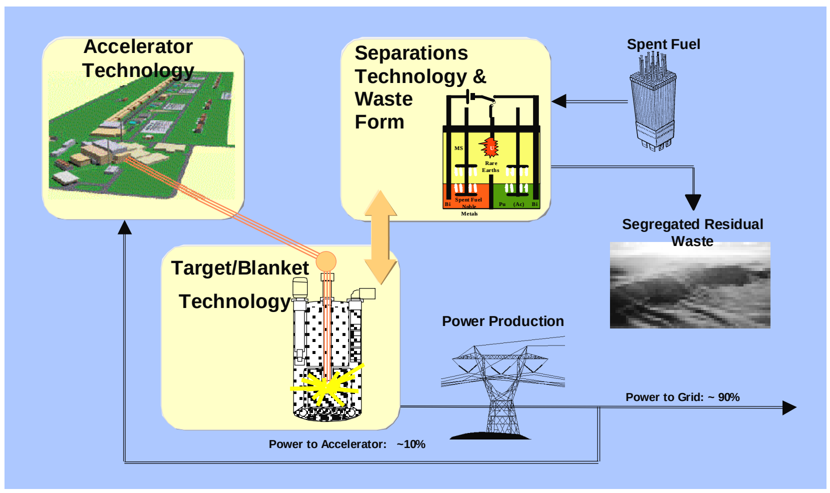


Fig. 3-1. Components of an ATW System

This section summarizes some of the options for the accelerator and target/blanket systems that are the components of accelerator-based systems for the transmutation of waste (ATW). More detail is given in Appendix B.

It is important to recognize that viable systems can be designed with virtually all combinations of the options presented here and in Appendix B. The options presented will have desirable and undesirable features, and the system designer must develop and optimize a given system/concept by considering various performance measures including waste-burner capabilities, cost, safety, technical maturity/risk, etc.

A number of approaches have been considered over the years for accelerator-based transmutation of waste systems. In general, the accelerator driver for these systems has been limited to consideration of linear accelerators and cyclotrons which are most capable of achieving the beam powers required to drive transmuters to powers in the 1000-MWt range with k_{eff}~0.95 - 0.98.

While there has been a common assumption that the actinide waste to be transmuted would be in the form of a sub-critical, reactor-like configuration, many options for the actual geometric layout, the form of the waste (e.g., solid or liquid) and other aspects of the system are possible. These range from having the protons impinge directly on the 'transmutation module' to the currently preferred approach of a separate neutron-producing target, surrounded by a blanket containing the material to be transmuted.

Transmutation of actinides requires fission since the actinides require a reduction of about 10 nucleons to reach a stable isotope. Transmutation of ^{99}Tc and ^{129}I is done by neutron capture which is followed by a quick decay to a stable isotope. There is general agreement [3-1, 3-2] that a high neutron flux is desired. High flux levels will allow fissioning of ^{243}Pu before its decay to ^{243}Am. One study that compared the effectiveness of various combinations of flux level and spectral characteristics[3-3] concluded that a thermal spectrum with flux levels of approximately 10^{16} n/cm^2-s would be the most efficient at transmuting minor actinides and long lived fission products (^{99}Tc and ^{129}I). Systems such as light water reactors and fast reactors were not capable of this level of performance, and it was concluded that an accelerator-based system would be the most realistic choice to achieve such flux levels. However, it was also recognized that it would be difficult to achieve such fluxes in a practical system, and that radiation damage would be a major issue/challenge.

3.2 Accelerator Options

The accelerator power required to achieve a desired sub-critical target fission power depends on the blanket k_{eff}; and drops dramatically as k_{eff} approaches 1.0. Since the accelerator beam power is the product of the final proton energy and the beam current, the optimal combination is the result of an optimization including consideration of accelerator performance, cost, and neutron yield as a function of proton energy for constant beam power. A related consideration is proton damage to the window and other components. In the energy range of a few GeV the damage is relatively insensitive to the energy of the particle; therefore reducing the current and increasing the energy is beneficial. There are two fundamental types of accelerator, linear and circular. The relevant features of each are described in Appendix B. Generally the high power requirements of the ATW will tend to lead to a preference for a linear accelerator.

3.3 Target Options

The primary design objective of the spallation neutron producing target is to maximize usable neutrons produced per incident proton (n/p). The neutrons per proton depend on the target design but, for the targets under consideration, ranges from 25 to 30 neutrons/proton. Differences in the geometric design of the target can cause greater differences in the production rate than differences in the materials being considered (W, Ta, Pb, Bi, Hg).[3-4]

A high production rate is not the only concern in maximizing the usable neutrons since the target material itself can absorb some of the neutrons. Another issue in producing usable neutrons is the spread of neutrons over the fuel axially. If the neutrons are produced over a small area there could be power peaking problems and cooling complications. If the neutrons are produced over too large an area there can be excessive axial leakage.

In a transmuter the target converts about 10 MW of proton energy into neutrons. This is a large thermal load that must be managed. The following four options have been considered for cooling the target:

- A solid target cooled by a dedicated coolant loop
- A solid target whose coolant is then also used as the “primary coolant” for the blanket.
- A liquid metal target in an isolated loop
- A liquid metal target which then also serves as the “primary coolant” for the blanket

The primary disadvantage of the second and fourth options is that the coolant for the blanket is in the proton beam, and hence will contain spallation products. These contaminants would then be circulated and might adversely affect the integrity of the blanket by interacting with the fuel cladding.

Tungsten and Tantalum are reasonable options for solid targets for ATW designs. Other targets such as solid lead, uranium, and the other actinides are also possible, but may result in thermal design problems. The cooling for the solid targets can be done using a separate cooling loop or by using the primary coolant. Direct cooling of the target with the primary coolant implies some spallation products will be in the primary coolant. In the case of sodium coolant the primary concern will be ^{7}Be which has a 53 day half life. If lead or lead-bismuth eutectic is the primary coolant, the spallation target can be the primary coolant. The system only requires the proton drift vacuum tube to be placed down the center of the blanket and a metal cap to separate the vacuum from the primary coolant.

Using a separate flow loop for a liquid target has the advantage of isolating the spallation products from the primary coolant. This would ease some of the chemistry control/corrosion concerns in the primary coolant loop for the blanket, as well as the radiological impact of the spallation products. The flowing liquid metal target options which can be considered for the ATW application include lead, mercury, and lead/bismuth eutectic.

The target window assembly separates the proton drift tube vacuum from the heavy metal neutron source target. In the case of the reference design the heavy metal target is a lead-bismuth eutectic. The window is thus exposed to the full proton beam, and an intense flux of secondary radiation (neutrons, pions, gamma-rays etc.). It will therefore be subject to radiation damage by this radiation field, which will have energies well in excess of the fission and fusion reactor experience. Currently, the basis of most radiation damage experience is driven by requirements set by fission and fusion reactor designs. Several experimental programs have been undertaken in connection with the APT program, and in addition spent targets from spallation neutron sources have been examined.

A materials research and development program aimed at window materials and their behavior in an ATW needs to be included in the overall research and development effort. In addition to reactions between the lead/bismuth and the primary window, irradiation by fast neutrons and protons causes changes in the material properties due to atomic displacements, and generates hydrogen and helium gas. These damage mechanisms are unique to spallation sources, since they are caused simultaneously by both neutrons and protons, and experience from reactors does not apply. An experimental program should be started as soon as possible in order to develop the necessary data base to design a credible ATW window arrangement.

3.4 Fast Spectrum Blanket Options

As noted in the previous section, the coolant for the blanket can either be separate from, or integrated with that of the target. Selecting the coolant depends on a number of factors including thermal/mechanical, chemical and nuclear characteristics. The thermal/mechanical characteristics include the heat capacity, density as a function of temperature, viscosity, and the phase change characteristics such as the melting and boiling points and the change in volume associated with a phase change. From these characteristics it is possible to infer the relative performance of passive safety features such as natural convection cooling. The chemical properties of a coolant concern issues of corrosion, toxicity, and energetic reactions (fires or explosions). The nuclear characteristics of a coolant are important to production of radioisotopes, use as a spallation source, and impact on the neutron spectrum.

For fast spectrum nuclear systems liquid metals are the main choices for coolants (although gas is also feasible).

Lead-Bismuth (PbBi) forms a eutectic at 55.5 wt. % Bi and 45.5 wt. % Pb. The creation of the PbBi eutectic reduces the melting points from 327 C and 271 C for lead and bismuth respectively to 123.5 C. PbBi is a good spallation source so the spallation target can be integral to the coolant. PbBi has been used in Russian submarine reactors. The thermal mechanical properties of PbBi provide for a large operating temperature range (melts at 123.5 C and boils at 1670) so that guarding against boiling is easy. The boiling point of PbBi is 167 C so there is a large operating temperture range and boiling is unlikely. In addition, PbBi is chemically inert so some accident concerns are reduced.

Some other advantages of PbBi are:

- Low vapor pressure at operating conditions.
- High atomic weight results in a hard neutron spectrum and hence improved fission cross section for minor actinides as well as a higher neutrons per fission.
- Low capture, therefore good neutron economy (usable neutrons to drive the transmuter/subcritical blanket)
- Good neutron reflector and gamma shield.
- Retains most actinides and fission products if released into the coolant.
- Small volume change with solidification.

Of course, as with any option, there are some undesirable features of PbBi. The three primary concerns are its corrosiveness, its radioactivity after irradiation and its toxicity. PbBi can dissolve steels and can be contaminated by solid admixtures due to interactions with construction materials. This corrosive concern has been handled in Russia by the development of appropriate materials and the use of oxygen control to allow a protective oxide coat to form for protection of the materials. The oxygen control is sensitive since both too much oxygen and too little oxygen can cause problems. The Russians have, through experience, solved this problem for use in submarine reactors but these systems did not have spallation products in the coolant.

Bismuth plus a neutron creates ^{210}Po with a half-life of 138 days. This half life is short enough that it is not a waste concern but it is an operational concern. Fortunately, ^{210}Po stays in the PbBi coolant as PbPo which self shields the ^{210}Po. In addition, Lead and Bismuth are both heavy metal poisons which will require adequate separation from the environment. When irradiated, they represent a "mixed" waste which further complicates disposal.

Another coolant option for a fast spectrum system would be to use molten lead. This would prevent the radiological hazards from ^{210}Po . The key disadvantages for lead are due to its high melting point (327 C). This higher temperature exacerbates the corrosion problems seen with lead-bismuth systems and it requires more complex systems for maintaining and achieving the molten state. Lead has a slightly lower spallation neutron yield than bismuth and lead coolant costs are lower by a few million dollars. A comparison of lead versus lead-bismuth can be found in Reference 3-5.

Sodium has been the coolant traditionally used for fast reactors. Years of fast reactor experience have lead to high confidence in designs using a sodium coolant. It does not have the corrosion concerns that exist with PbBi coolant. However, PbBi has significant advantages over sodium due to its high margin to boiling and lower chemical reactivity with air and water. Further, sodium is not a good spallation neutron source so a separate target would be required. Clearly, ATW systems can be designed using sodium and there would be lower uncertainty in the system due to the larger experience base with sodium.

There are a few other, less important, differences between PbBi and sodium. Sodium melts at 98 C compared to 123.5 C for PbBi. Sodium has a lower density so structural costs may be lower. The chemical and biological hazards (and disposal issues) of sodium are less than for PbBi. The activation product ^{24}Na has a half life of 15 hours compared to the ^{210}Po half life of 138 days (however the self shielding of the PbBi helps mitigate the concern). Finally, the sodium coolant in the system costs a few million dollars less than the PbBi.

Helium can also be used to cool a fast reactor. Helium has a number of properties that make it desirable as a coolant for the ATW. Helium;

- Is chemically inert.
- Has no phase change.
- Is transparent to allow easier visual access to the fuel and structures.
- Does not absorb neutrons. Hence it produces no radiological concern.
- Is non-corrosive.
- Allows direct use of a gas turbine for conversion to electricity.

The key undesirable feature of helium cooled systems is the high reliance on the pressure boundary. Normally, loss of pressure boundary concerns are compensated for by fuel with a high thermal inertia. There is a particular concern over the pressure boundary between the accelerator beam tube, which is maintained at a vacuum, and the primary coolant.

3.4.1 Blanket Fuel Options

For a liquid metal cooled fast spectrum system traditional fuels are oxides and metals. There has also been a long-term interest in carbides and nitride fuels. Since ATW fuel will not contain large amounts of fertile material, the Doppler temperature feedback is small. A number of options for addressing this issue have been proposed for critical systems. It may be desirable to investigate some of the Doppler feedback fuels for ATW.

Metal fuel has good thermal properties which make it attractive for use in fast spectrum systems. The Integral Fast Reactor Program used metal alloys of Uranium, Plutonium and Zirconium, successfully. The original swelling problems that limited the burnup of metal fuel in EBR-II to 2% were overcome by using a lower smear density (75%) and burnups of 20% were reached. Metal fuel is also ideal for pyrochemical processing.

Oxide fuels formed the mainstay of the fast reactor program. They have a lower conductivity than metal fuels but this is compensated by a much higher melting point. As a ceramic they are more susceptible to damage in thermal transients; however, they also have attained burnups of about 20% without difficulty. World-wide there is a very large database of oxide fuels.

Nitride fuel has good thermal properties and can be used with pyrochemical processing. Traditional nitride fuels are being studied for use in burning just the minor actinides (MA) and using the plutonium in fast or thermal reactors. If the fuel cycle is changed to use an ATW for MAs then nitride fuels would be considered.

In transmutation applications, the ^{238}U is not present in the fuel. This is to prevent the creation of more TRU at the same time as it is being destroyed. The lack of ^{238}U reduces the Doppler temperature reactivity coefficient to near zero. Since the Doppler feedback is very important to the inherent safety of critical systems, some have concluded that a critical system without ^{238}U would not be safe. (Systems using highly enriched uranium have been operated extensively. These systems have very low Doppler feedback but have been designed to utilize other temperature feedbacks such as thermal expansion or moderator temperature feedbacks.) Analysis has been performed to design systems with Doppler feedback from isotopes other than ^{238}U.[3-6, 3-7]

The objective of the ATW is to burn all the transuranics together and some method of dilution of the fissile material must be done to prevent criticality. In the reference case this is done by use of a low weight percent of TRU in the fuel. This could be done by making cermet fuels.

Cermet fuels promise operational and safety advantages compared to oxide fuels, principally lower fuel temperatures, high geometric stability, and improved behavior on irradiation. These advantages stem primarily from the fact that the fuel “kernels” are in direct contact with, and “uniformly” dispersed within a metallic lattice, and the space between the cermet and the clad is filled with a metal alloy. Consequently, the heat transfer from the fuel to the coolant are enhanced, and the operating temperatures and thermal and mechanical stresses in the rod are reduced. Since fission products are retained within the fuel porosity and metal matrix, swelling/bowing are minimized, as is the potential for fission product release. These factors all contribute to enhanced safety. The possibility of pellet-clad interaction is eliminated, and clad corrosion is reduced, thereby allowing high burnups with attendant reductions in fuel-cycle costs and waste storage requirements. The experience base with fuels of this type for thermal or fast reactors, however, is limited.

Two types of particle fuel that have been investigated in the U.S.: sol-gel based graphite kernels, coated with silicon carbide, and developed by General Atomics into BISO/TRISO variants and utilized in High Temperature Gas Cooled Reactor (HTGR) fuel; [3-8] and the Infiltrated Kernel (IK) approach developed by BNL in the SNTP program.[3-9]

Sol-gel was developed by the HTGR program, and has been demonstrated for uranium and plutonium carbides, oxides and oxy-carbides. Other actinides should be similar in principal. The IK kernel was demonstrated for uranium but it is should be usable with other actinides because of similar chemistry. Other materials (e.g., fission products such as Tc or I, or burnable poisons) should be feasible provided a stable carbide form exists.

It has been demonstrated that sol-gel particles can survive high burnups (~100,000 MWD/T-AVR). For the IK kernel, high burnups are likely because of the internal porosity of the graphitic structure, and burnups of up to ~100% should be possible by suitable adjustment of the internal porosity.

3.5 Fuel Processing Options

The technical details on fuel processing options are provided in "Part II: Technical Analysis and Systems Study" of the Separations Technology and Waste Form Technical Work Group Report (STWF TWG). The current reference approach is to perform aqueous processing on the commercial spent nuclear fuel at a single facility. Many aqueous options are discussed in the STWF TWG report. The aqueous options are preferred over pyrochemical techniques for the front-end since the fuel is cool (average time since discharge in excess of 20 years) and the volume of fuel to be processed is large.

The pyrochemical separation technique is the reference processing technique for the recycled ATW fuel since the volume is small and the expected cooling time is short. The pyrochemical separations are expected to be performed at the ATW sites.

3.6 Fission Product Transmutation Options

The reference ATW design will transmute ^{99}Tc and ^{129}I by absorption of a neutron. The design of the target material is under development but several issues can be addressed. ^{99}Tc plus a neutron becomes in the order of tens of seconds stable ^{100}Ru which has similar physical properties to ^{99}Tc. However, ^{129}I plus a neutron becomes ^{130}Xe in the order of tens of hours and ^{130}Xe is a noble gas. In the case of ^{99}Tc a target can be developed that will allow a very long residence time. In the case of ^{129}I pressure buildup is a concern which must be accounted for in the target design and could limit the target life.

In order to help the transmutation of ^{99}Tc and ^{129}I, some moderation of the flux is necessary. Unfortunately due to high thermal fission cross section of the TRU, thermalization of the neutrons can result in local power peaking problems.

It should be pointed out that one could consider not transmuting ^{99}Tc or ^{129}I but rather placing them in a long life container. The ^{99}Tc has a half-life of 213,000 years. Some have proposed that containers can be developed that can prevent ^{99}Tc from reaching humans before it decays. Unfortunately, ^{129}I has a 15,700,000 year half life and it is not believed that a container can be designed to last long enough to contain the ^{129}I however, gradual release of the ^{129}I over a long time frame would not exceed currently expected dose requirements.

3.7 Reactivity Control Options

As the fuel burns in the reference ATW design there is a large change of reactivity. There are several options to compensate for this change in reactivity. The following is a list of some of the reactivity control options:

1. Allow a decrease in power associated with the decrease reactivity.
2. Increase the accelerator beam power to compensate for the change in the reactivity.
3. Remove some absorber material to compensate for the change in reactivity.
4. Use frequent fuel shuffling and reloading to minimize the impact.

In all the cases the use of some type of burnable absorber is desirable.

3.8 Alternative System Designs

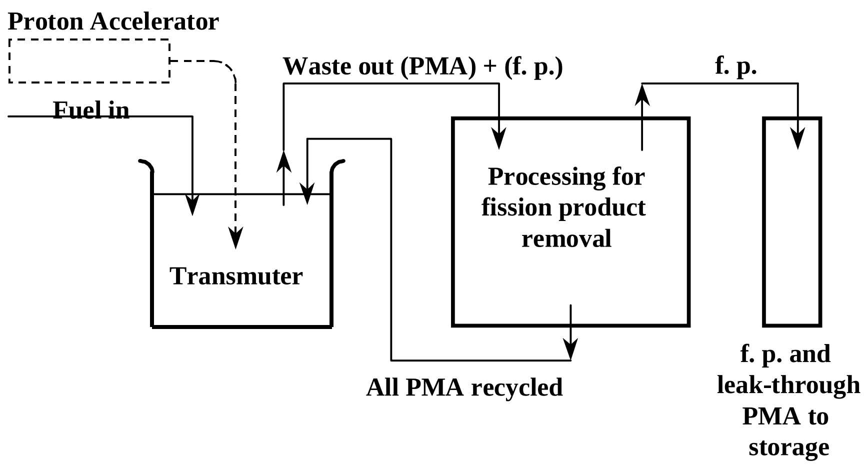
The reference design for this study uses a fast spectrum and clad fuel fixed in position, see Section 4.0. Most of the options discussed above support this reference ATW design. However, other designs have been proposed that are radically different than the reference design and are best explained by a description of the entire system.

3.8.1 Thermal Spectrum Molten Salt ATW Design

A thermal spectrum molten salt ATW design has been described in Reference 3-10. The system design utilizes NaF-ZrF carrier salt. Fig. 3-2 compares the steps anticipated in a molten salt ATW as compared to the reference ATW. Fig. 3-3 shows the anticipated system. Fig. 3-4 shows a vertical slice of the reactor design and Fig. 3-5 shows a top view. The advantages of this of this design are:

1. No backend chemistry. Once the fuel is fluorinated it is maintained in the core until discharge.

REFERENCE APPROACH



MOLTEN SALT APPROACH

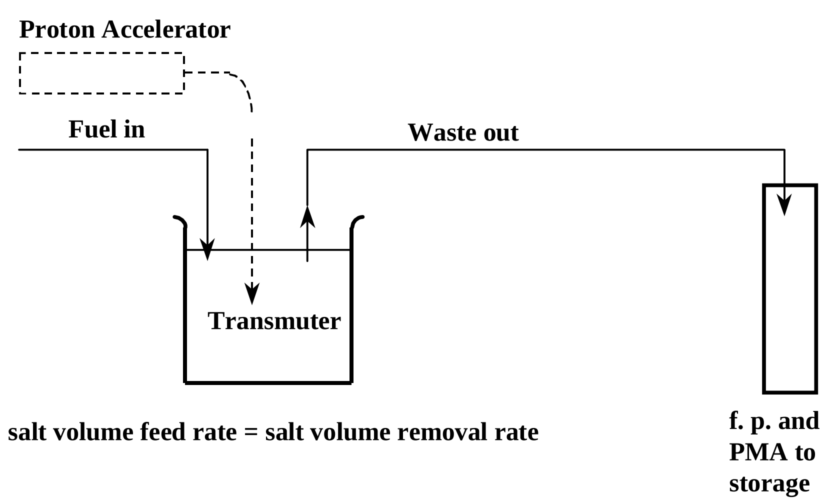


Fig. 3-2. General system schematics comparison between the molten salt ATW Compared to the reference ATW

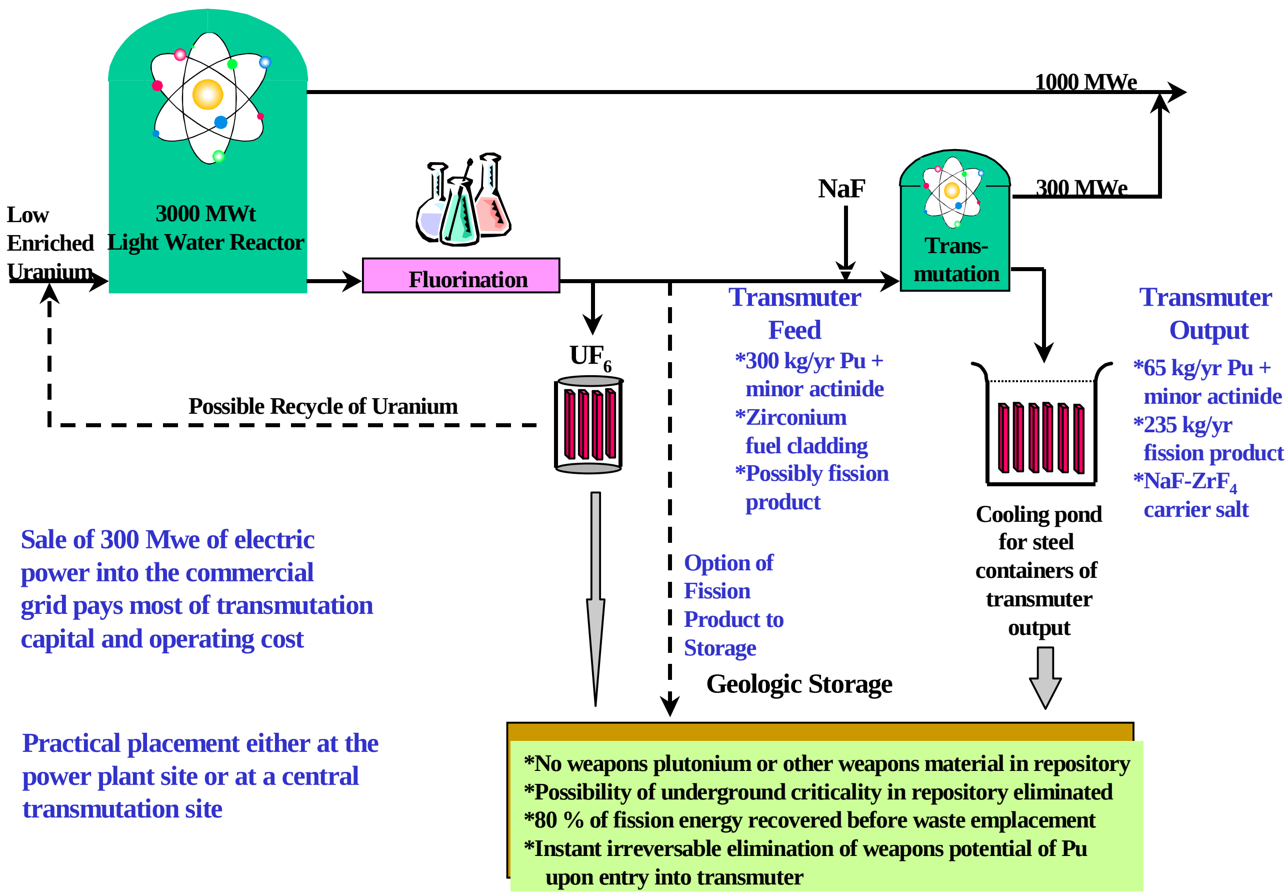


Fig. 3-3. Flow diagram of a system using molten salt ATWs

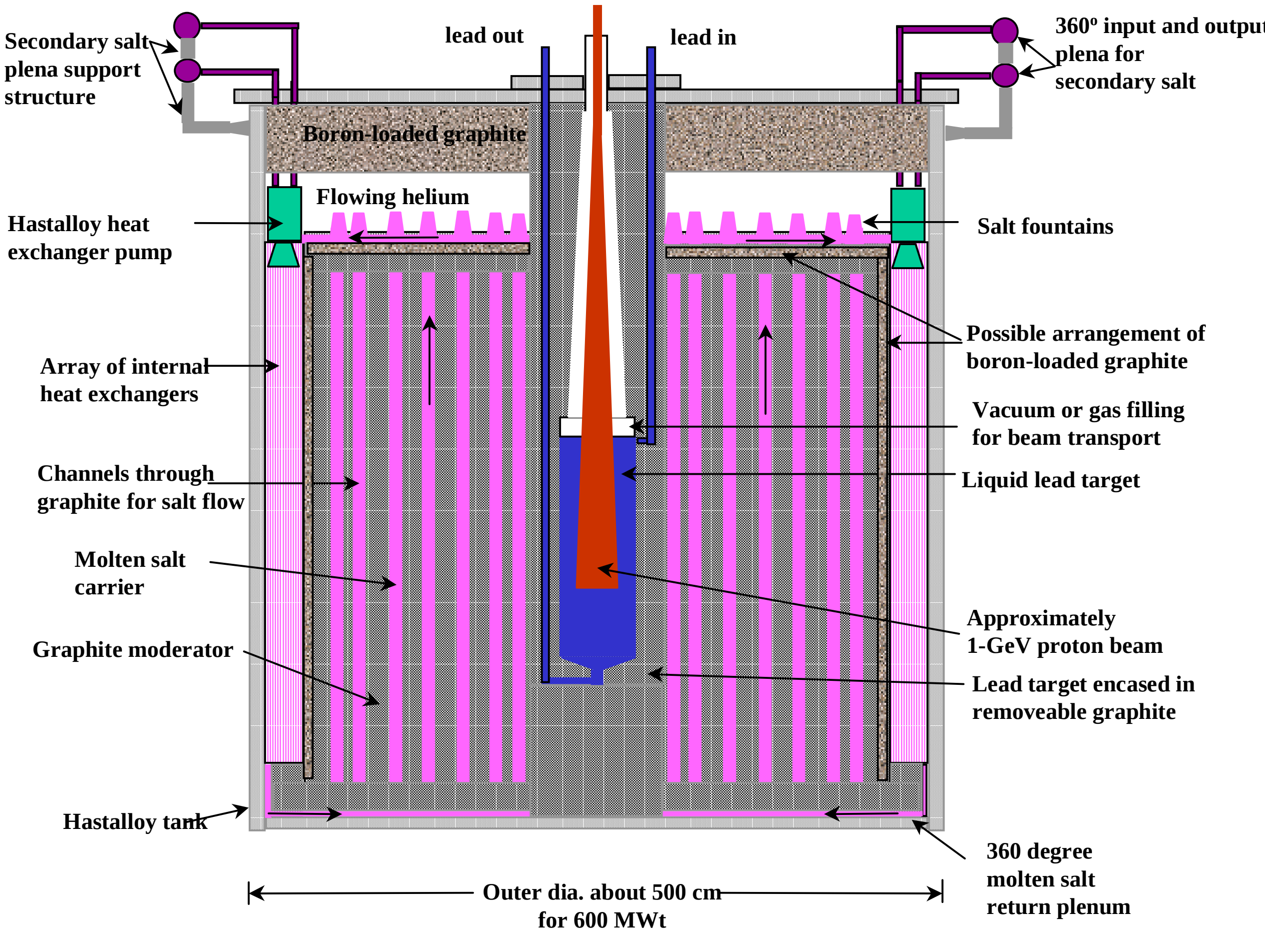


Fig. 3-4. Molten Salt ATW (side view)

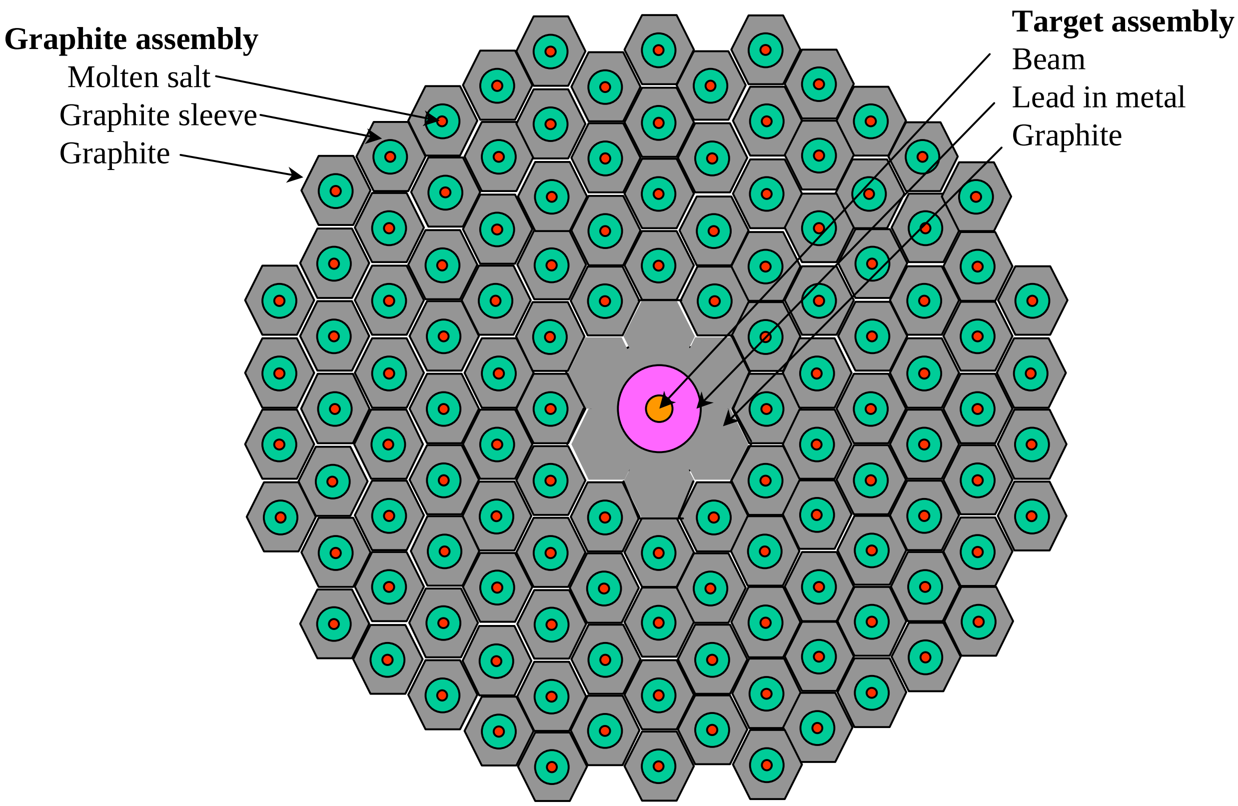


Fig. 3-5. Molten Salt ATW (top view)

2. Immediate denaturing of the plutonium once mixed with the molten salt of the core. The denatured plutonium would be difficult to use as a weapon material.
3. Due to the homogenous nature of the fuel the reactivity change with burnup can be minimized by continuous feed/bleed cycles.
4. Low inventory of TRU. Since the system uses a thermal spectrum the molten salt has a very low concentration of TRU and the total inventory is much less than for fast neutron systems. This would allow the deployment of more ATW machines for a given quantity of TRU and hence a fast depletion of the TRU (also a greater power generation rate).
5. No need for fuel fabrication.
6. No lead coolant and hence reduced heavy metal toxicity.
7. Uses molten salt technology developed in the U.S.

The disadvantages are:

1. Liquid fuel. This is the reduction of one fission produce release barrier but there is no reason equal safety cannot be achieved.
2. Corrosive fuel. Although this was a problem with the original molten salt reactor, corrosion resistant materials have been developed for molten salt operation.
3. Mixing of fuel implies that 20% of the actinides remain at discharge. A second tier of reactors could be developed to reduce the actinides more.
4. Less neutron economy with a thermal spectrum. The neutrons per fission are about 7% less at thermal energies. The parasitic losses to fertile actinides are about a third greater for thermal systems. This would imply either a higher power accelerator or use of a higher k_{eff} during operation. A higher k_{eff} may be reasonable due to less change in reactivity during burnup.

3.8.2 Blanket based on BNL Particle Bed Reactor (PBR)

The achievement of a high neutron flux level which is desirable for efficient burning of waste implies a correspondingly high power density in the fissile material, and a rapid decrease in reactivity.[3-11, 3-12, 3-13] Efficient transmutation of plutonium/actinides thus requires efficient heat removal, and reactivity control. Heat removal and transfer from solid elements to an appropriate coolant is proportional to a product of a heat transfer coefficient, the heat transfer area, and the thermal gradient. The second parameter is controlled by the element geometric design. It can be shown that for any practical dimension (rod diameter, plate thickness, and sphere diameter) randomly packed spheres offer the highest area/unit volume of any geometric arrangement; this property was exploited in the PBR design developed by BNL in the late 1980s/early 1990s for space applications (SNTP program). In view of this property an attractive option for the sub-critical blanket is to base the plutonium/actinide bearing elements on randomly packed spheres. Reactivity control can be enhanced by adding burnable poisons or fertile material to the fuel element. The addition of these materials will reduce the anticipated rapid drop in reactivity, and lengthen the cycle time. In an accelerator based system this effect can be partially compensated for by increasing the proton beam current, however, the possible increase in beam current, is limited and is a function of the accelerator design and economic considerations. In addition, due to the high flux levels in ATW systems, the buildup of ^{135}Xe

following shutdown of the system can result in a large amount of negative reactivity. This negative reactivity must be compensated for if a startup is desired within approximately one week following shutdown. In this case it would seem prudent to account for the buildup of ^{135}Xe in the fuel-management algorithm. A simple fuel-management algorithm which includes out-of-target storage of approximately one week prior to re-introduction of the fuel particles should be sufficient to allow decay of the ^{135}Xe.

The basic building blocks of an ATW based on the PBR are shown in Figs. 3-6 and 3-7. The transmuter would employ target elements consisting of particles, similar to those used in the High Temperature Gas Cooled Reactor (HTGR). In the current application the diameter of the particles is 5 mm, which is approximately ten times larger than the HTGR application. Each particle consists of a central graphite kernel containing the fissile material or fission product, and is coated with layers of pyrolytic carbon and metal carbide or silicon carbide, as deemed necessary to be compatible with the coolant, and to contain the fission products. These particles are expected to contain the fission products more efficiently than HTGR particles, since they have a very low inventory of fissile material and a substantial internal porosity, and thus the pressure due to volatile fission products will be correspondingly lower and more easily accommodated. In contrast to the HTGR, these particles would be cooled directly by the coolant. The coolant can be either gas (pressurized helium), light water, or a liquid metal (sodium, lead etc.). The choice of coolant will be based on whether a fast or thermal spectrum target is being investigated, and will determine the outer protective particle coating materials.

Each individual particle can be interrogated to ensure that the desired degree of burn-up of the waste nuclides has been achieved. The particle nature of the fuel offers the potential for on-line re-fueling (similar to that employed in the German Pebble Bed reactor) which provides additional flexibility for reactivity control, as well as multi-pass operation. The particulate form also offers a high-integrity final disposal option requiring no additional processing; the particles can be encapsulated in a graphite/pitch matrix in a container which can then be placed in a suitable repository.

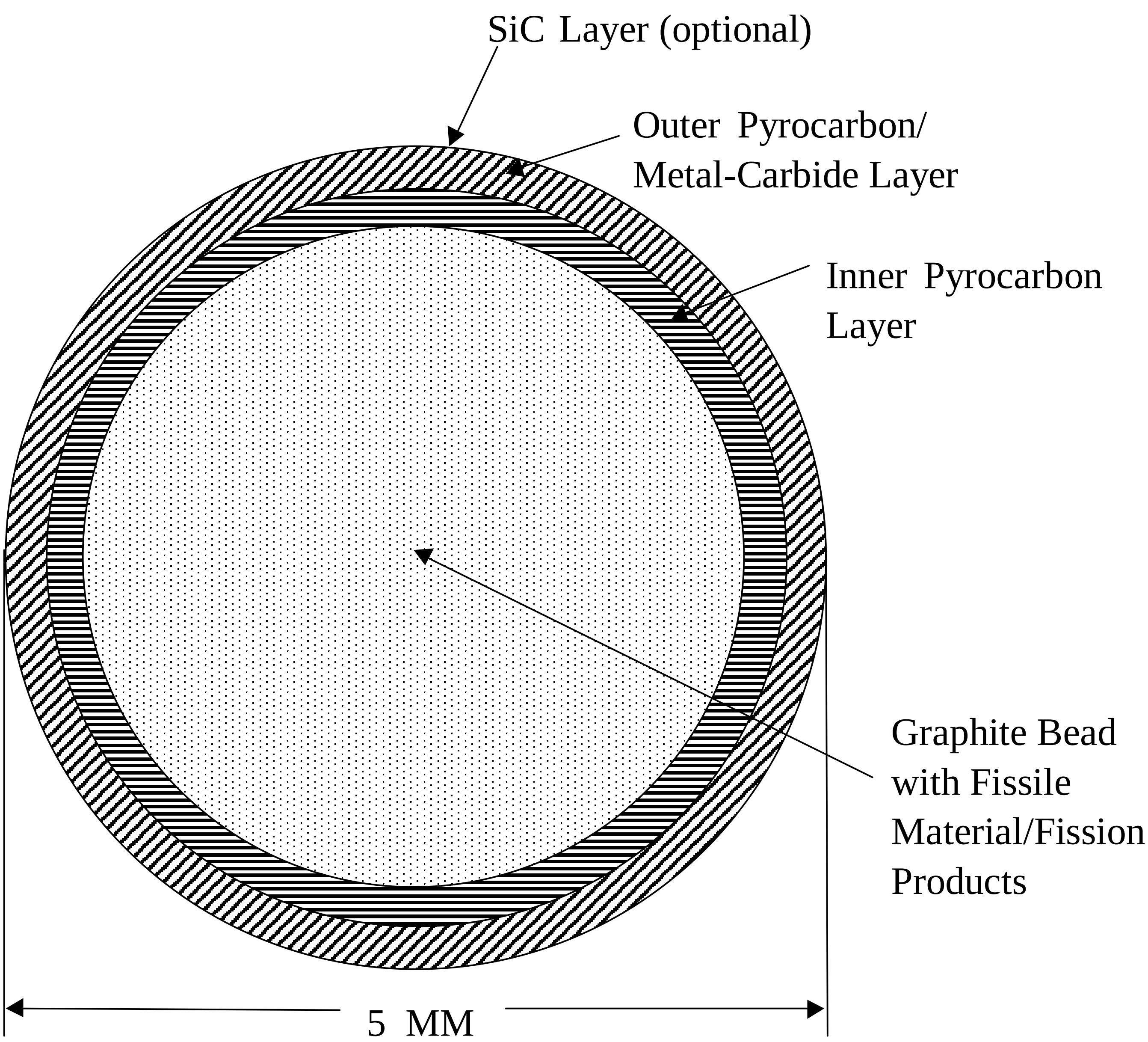


Fig. 3-6. Typical Coated Particle

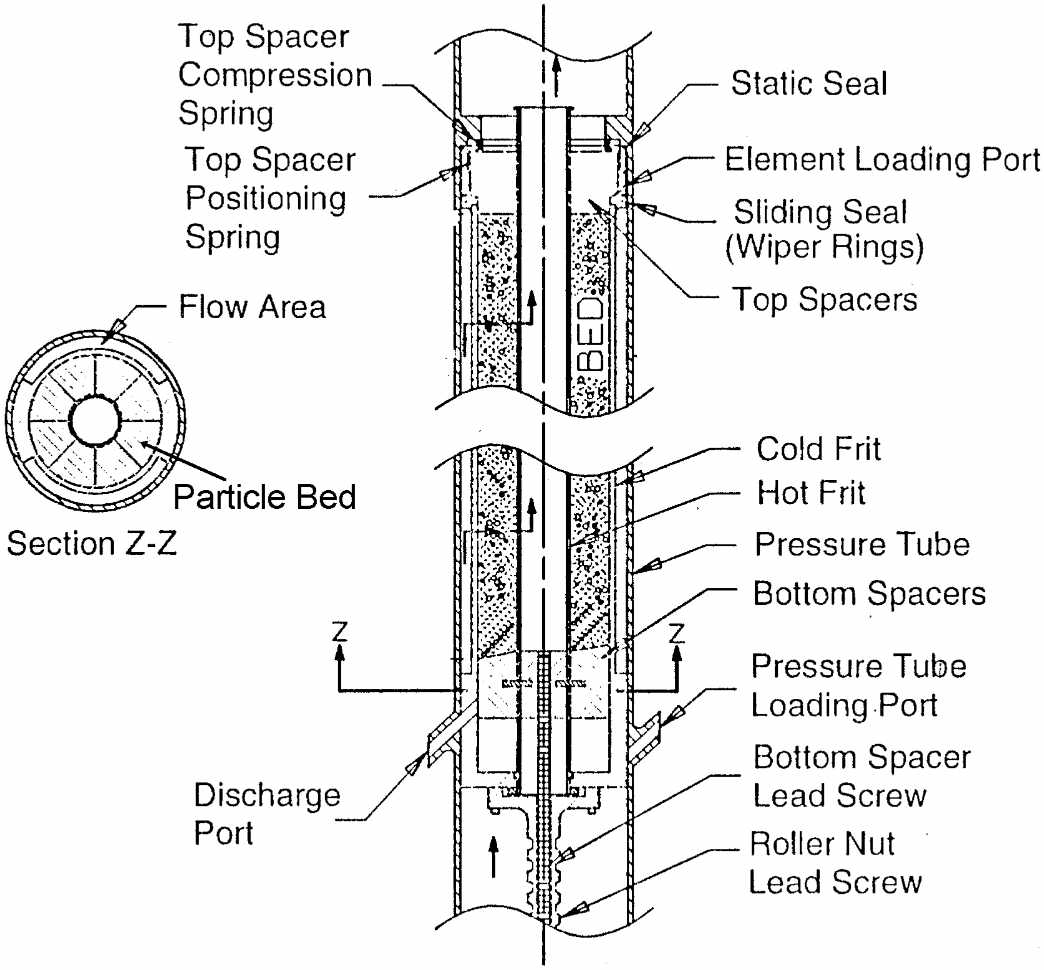


Fig. 3-7. Blanket/Burner Fuel Element

References

[3-1] J. R. Powell, et al., “Elimination of Weapons Grade Plutonium Via Burning in a Particle Bed Reactor,” Proceedings of the International Conference On Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options, September 12-17, 1993, Seattle, Washington, 1219-1225. American Nuclear Society.

[3-2] T. Iwasaki, et al., “Fast and Perfect Transmutation of Actinide Waste using A-Burner,” Proceedings of the International Conference On Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options, September 12-17, 1993, Seattle, Washington, 622-629. American Nuclear Society.

[3-3] H. Küsters, and H. W. Wiese, 1991. “Burning of Actinides and Fission Products in Reactors and in Accelerator Driven Spallation Sources,” Transactions of the American Nuclear Society, **64,** 544-6**.**

[3-4] G. J. Russell, E. J. Pitcher, and L. L. Daemen, 1995. “Introduction to Spallation Physics and Spallation-Target Design,” LA-UR-95-817, Los Alamos National Laboratory.

[3-5] H. Sekimoto, and Z. Su’ud, 1995. "Design Study of Lead- and Lead-Bismuth-Cooled Small Long Life Nuclear Power Reactors using Metallic and Nitride Fuel." Nuclear Technology, **109**, 307-313.

[3-6] G. Chang, 1998. “Neutronic and Burnup Characteristics of an Actinide-Reduced Plutonium Fuel with Tungsten.” Annuals of Nuclear Energy, **122**, 43-51.

[3-7] J. M. Paratte, and R. Chawla, 1995. “On the physics feasibility of LWR plutonium fuels without uranium.” Annals of Nuclear Energy, **22**, 471-81.

[3-8] R. A. Knief, <u>NUCLEAR ENERGY TECHNOLOGY – Theory and Practice of Commercial Nuclear Power</u>, McGraw-Hill Book Company, New York, (1981).

[3-9] H. Ludewig, J. R. Powell, M. Todosow, G. M. Maise, R. Barletta,and D. G. Schweitzer, “Design of Particle Bed Reactors for the Space Nuclear Thermal Propulsion Program,” Progress in Nuclear Energy, Vol. 30, No. 1, pp 1-65, (1996).

[3-10] C. D. Bowman, 1998. “Accelerator-Driven Systems for Nuclear Waste Transmutation.” Annu. Rev. Nucl. Part. Sci., **48**, 505-556.

[3-11] J. R. Powell, et al., “Elimination of Weapons Grade Plutonium Via Burning in a Particle Bed Reactor,” Proceedings of the International Conference On Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options, September 12-17, 1993, Seattle, Washington, 1219-1225. American Nuclear Society.

[3-12] T. Iwasaki, et al., “Fast and Perfect Transmutation of Actinide Waste using A-Burner,” Proceedings of the International Conference On Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options, September 12-17, 1993, Seattle, Washington, 622-629. American Nuclear Society.

[3-13] H. Küsters, and H. W. Wiese, 1991. “Burning of Actinides and Fission Products in Reactors and in Accelerator Driven Spallation Sources,” Transactions of the American Nuclear Society, **64,** 544-6**.**

4.0 TECHNICAL REFERENCE FOR ATW

The ATW technical reference reflects the current national and international thinking as to the best technology options and size of the facility. However, there are various technology options still under discussion worldwide, and several potential backup or advanced technology options have been identified (see Section 3). Optimization of the size and configuration will be a lengthy iterative process as the design teams explore and evaluate options. Therefore, the reference design described here should be viewed as a preliminary implementation that will undergo continuous evaluation and change.

ATW technology is driven by the problematic materials- what they are and in what quantities. To size an ATW system to consume the spent fuel legacy, an assumption is made that the current generation of nuclear power reactors continues to operate until their operating licenses expire, but that no new plants are licensed and that there are no license extensions for existing plants. The assumption of no advanced reactors that might consume some of the plutonium implies that the entire plutonium inventory would be consumed in ATW. In addition, it is assumed that the mission should be completed in a manner that is both cost-effective and expeditious, preferably within about a century.

Although only about 1% of the spent fuel mass needs to be transmuted in ATW systems, the energy in those materials is enormous. It is this large amount of energy that determines the size of an ATW system. Although the ATW mission is to transmute the long-lived wastes, revenues from that energy are essential to pay for the full ATW system deployment. Effectively, one is constructing large nuclear energy systems that are accelerator-driven to safely operate with the waste stream based fuel.

4.1 Basic Technology Choices

The ATW system requires three major technologies, the accelerator technology to provide a high power beam of charged particles (protons), target/blanket technology needed to transmute the long-lived hazards into stable or short-lived materials and the chemistry processes that allows the materials to be separated. The reference ATW design is based on known technologies in each of these major areas, although some mission-specific requirements necessitate some modifications/extensions to current technology.

4.1.1 Accelerator

A linear accelerator is chosen for the reference design because of the high beam power requirements. Linear accelerators are believed to be capable of accelerating over 100 mA of protons to several thousand MeV, this implies that continuous beams in the few hundred megawatt range are practical. The other main option for high power beams, cyclotrons, are cheaper to build but are limited in both energy (relativistic effects) and current. As a result, cyclotrons appear to be fundamentally limited to a few megawatts of beam power. Although such beam powers may suffice to drive energy amplifier thorium-based systems, see Section 9, they do not appear sufficient for the currently envisioned U.S. application.

4.1.2 Target/Blanket

A few choices are required in the design of the target/blanket. A fast spectrum is chosen for two reasons. First, nearly all actinides will fission in a fast spectrum, giving maximum flexibility for the blend of fuel. In contrast, in a thermal spectrum some isotopes are fissile and some are fertile. Therefore the system reactivity changes significantly during the burnup process, almost forcing the designer to use liquid fuel forms with continuous refueling, which in turn raises significant safety issues. Second, the fast spectrum produces many excess neutrons that can be used to transmute iodine and technetium. In order to achieve a fast spectrum, a liquid metal is chosen as a coolant. Because there exists an extensive international experience base with sodium coolant, it is designated as the reference coolant. However, liquid lead-bismuth may offer significant advantages over sodium as both a spallation target and as a coolant, and is designated the preferred technology (and is to be developed aggressively).

The choice of sodium as the reference coolant allows for recent detailed cost studies of the ALMR (PRISM) design to be used as a reference in the life cycle cost part of the study. The choice of pyrometallurgical separation technology drives the design towards metal fuel. Although this metal fuel would have a different composition than traditional Integral Fast Reactor program metal fuel (75% Zr by weight as opposed to < 10% by weight in PRISM), the high zirconium content suggests this fuel should have some very desirable characteristics, including the ability to tolerate high burnup levels.

Structural materials and cladding must be compatible with the chosen coolants. With sodium coolant, inconel and HT-9 (a ferritic steel developed and tested as part of the ALMR program) are nearly ideal materials, with an excellent experience base that covers most conditions of interest. With liquid lead-bismuth, the Russians have had excellent success with a few steels, including one that is similar to HT-9. However, inconel is not compatible with lead-bismuth, so alternate materials would need to be demonstrated for the beam entrance window, where adequate performance in a high proton-irradiation environment must be a demonstrated capability.

4.1.3 Separations

In selecting a reference separation technology there are two primary options, the comparatively well-known aqueous separations and pyrometallurgical separations that provide some specific advantages useful for ATW. Because of its capacity for high through-put and its ability to provide a uranium stream that meets Class C Low-level waste requirements, an aqueous process named “UREX” is the reference technology for processing the “cold” spent fuel. An alternate path for processing the spent fuel based on pyrometallurgical separations may offer advantages including greater proliferation resistance, but requires some technology development.

After the initial separation of uranium, all further ATW separations and processing steps are based on pyrometallurgical processing. This choice is made for two reasons, namely, the bulk separations provide greater proliferation resistance and the pyroprocess is more tolerant of the high heat and radiation anticipated during the processing of fuel that has been irradiated in the ATW target/blankets. At the scale of the reference ATW plants, all separations, either aqueous or pyrometallurgical, will be modularized and constructed at the plant sites. This has the primary advantage of limiting all materials transport to either spent fuel from current nuclear power reactors or waste forms from ATW plants.

Although these assumptions are useful in defining a reference ATW system, there are clearly alternatives available. Should there be problems with the chosen processes, materials, or technologies, these alternate technology choices could be employed, often with minimal consequences. There are also instances where advanced technology options might be utilized in order to gain one advantage or another. Section 6 describes the R&D planned to confirm these choices and develop other technologies.

4.2 Sizing the System

The size of an ATW target/blanket facility for this study has been selected to be 840 MWt, for two reasons. First, it matches a version of the advanced liquid-metal cooled reactor (ALMR) known as PRISM for which extensive cost-analyses were performed**).** Because ATW transmuters are likely to physically resemble the ALMR units, the costs are likely to be similar. This choice then helps provide a firm basis for the estimate of the cost of ATW. Second, the ALMR system was the product of an extensive cost and safety optimization effort, and it is not unreasonable to expect that a similar effort for ATW transmuters would have similar results.

Starting from this size of transmuter the proton beam power is derived using the subcritical multiplier M, which scales with the inverse of $1\text{-}k_{eff}$. The parameter k_{eff} can only be finally determined after extensive physics and safety analyses, but is expected to lie in the range between 0.96 and 0.98. For this study we have assumed k_{eff}=0.97, which implies a proton beam power of about 11.25 MW is required to drive a 840 MWt transmuter.

Linear accelerators are more efficient and more cost effective if they are pushing high currents, as is the case for the Accelerator Production of Tritium linac. Further, accelerator beams are nearly always shared between multiple target facilities. Therefore, sharing a high power beam between more than one transmuter is economically attractive. It is relatively straightforward to divide a beam equally, using rf splitters, which makes sharing between 2, 4, 8, or 16 targets straightforward. (Note that the beam splitters cycle among the targets perhaps a hundred times per second, minimizing any potential transients in the targets.) For the reference case, it is assumed that two 45 MW accelerators drive eight 840 MWt transmuters, with cross-linking provided so one accelerator can support any four transmuters. This provides high likelihood that at least half of the total generating capacity with be available most of the time.

The separations processes are performed at two different scales. The front-end processing of spent fuel is a large-scale process (because of the large uranium inventory) and particularly suitable for aqueous treatment. However, regardless of whether and aqueous or a pyro-based front end is used to separate the uranium, the facility can be modularized and therefore scaled for the site requirements. In contrast, the back-end process for removing fission products from ATW spent fuel and reforming that fuel for subsequent irradiation can be much smaller and based on pyrometallurgical processing. Because pyrometallurgical processing is typically performed at a relatively small scale (many batches through small processing cells), it is easily scaled to support ATW unit throughput.

Lastly, it is necessary to estimate the ATW plant life-time. Accelerators are inherently modular and don't accumulate significant materials damage from radiation. As a result accelerators have an indefinite lifetime. Most separations processes are also inherently modular, and one can replace the equipment as necessary. In contrast, the transmuters are the most likely source of lifetime limitations. Over several decades, structural materials accumulate significant radiation doses, and some portions of the device could be difficult to replace. A sixty-year lifetime has been assumed, consistent with the objectives of most advanced reactor design efforts. The issue of replaceable components will be evaluated as part of the design process.

4.3 Reference ATW Plant

A reference ATW plant is illustrated in Fig. 4-1. It is sized according to some of the criteria discussed in Section 4.2. Details about the assumptions and computed performance of this system are provided in Appendix C.

Over sixty years of operation, the ATW reference plant would process 10,155 tn of spent fuel. This is in comparison to the current inventory of about 40, 000 tn of spent fuel and the projected inventory of 86,317 tn of spent fuel if all currently licensed nuclear power plants run until their licenses expire.

The configuration shown in Fig. 4-1 has attractive characteristics, but may be less than optimal. This layout has two large linear accelerators to provide proton beam to eight transmuters. This configuration allows transmuters to receive beam whenever at least one accelerator is operating, improving systems availability. Although the capital cost of this configuration may be modestly higher than the cost of one large linac driving eight 840 MWt transmuters, for example, it is thought the improved availability will bring a larger revenue stream from electric power sales, thus covering any additional investment.

The separations process illustrated includes three steps. If we assume the reference of an aqueous front-end, the first step removes the uranium via the UREX process. The second step is an oxide-reduction process, converting the wastes from oxide to metallic form. The third step then removes the transuranic components and converts them into ATW fuel form. For an entirely pyrometallurgical process, the first step is oxide-reduction, which convert the spent fuel from oxide form to metal form. It is at this stage that the iodine is isolated. The second step separates the uranium, reducing the spent fuel waste stream by roughly a factor of twenty. Technetium can be isolated at this stage. In the final step, the transuranics are separated from the remaining fission products.

Of the 10,155 tn of spent fuel, approximately 9684 tn of uranium can be first separated. Although some of this uranium could be recycled in power plants (it has higher fissile content than natural uranium), the assumption is that it would probably be discarded as Class C Low Level waste.

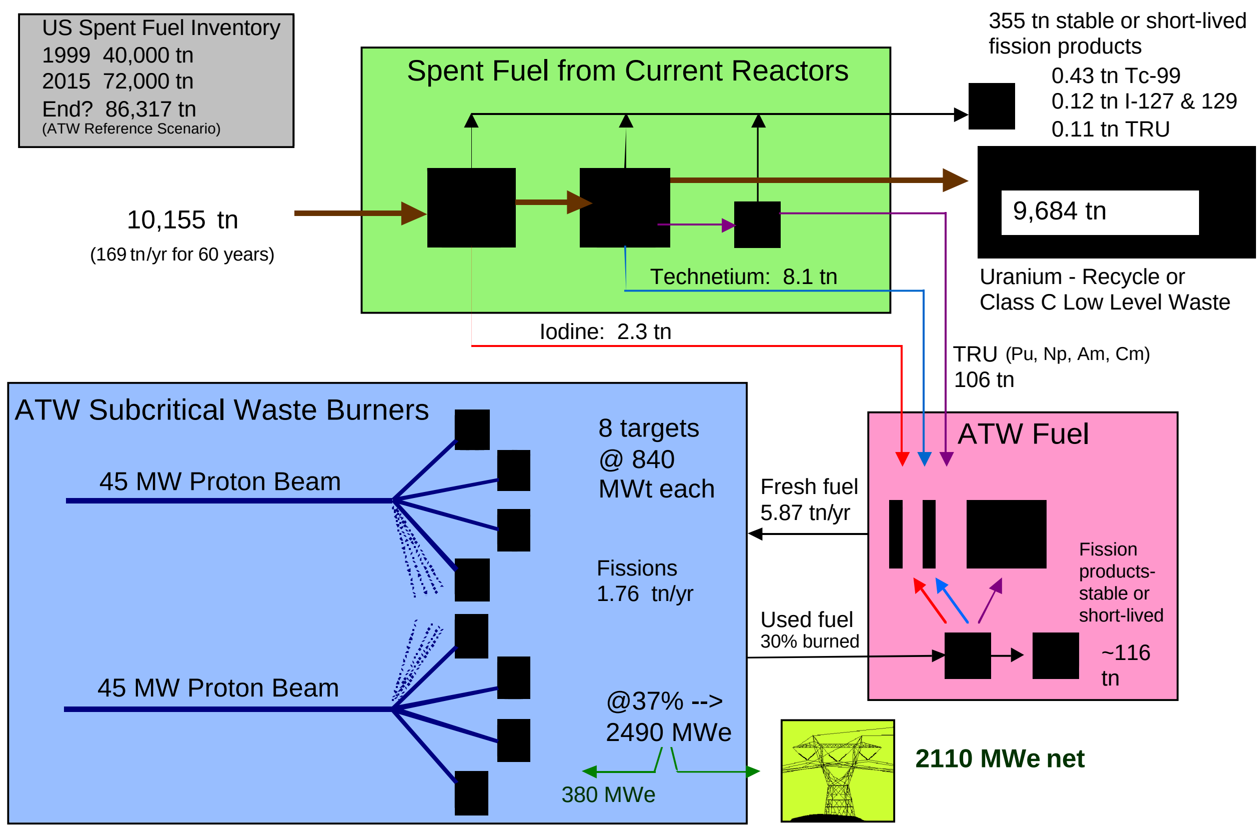


Fig. 4-1. Reference ATW plant sized to process 10,155 tn of spent fuel

Of the remaining 470 tn, about 355 tn are mostly stable, short-lived, or longer-lived but comparatively harmless isotopes. Also included is somewhat less than a tonne of technetium, iodine, and transuranic content that the separations process fails to fully separate. The 355 tn can be cast into long-lived waste forms that would resist dispersion by natural phenomena, including ground water penetration, leaching, and transport. The cesium and strontium products have roughly 30-year half-lives, so this part of the waste stream generates significant decay heat- for the first several decades. This portion of the waste stream does require long term disposal in some form of waste repository, although the requirements for isolation may be reduced.

The transuranics would be blended with zirconium (about 80 to 90 atom per cent) to form ATW fuel rods. The high zirconium content provides some advantageous fuel characteristics including high melting temperatures and good tolerance for fission gas build-up. The assumption for the reference case is that about 30% of the TRU content will be fissioned per pass through ATW, but it is hoped that much higher burnups (perhaps 50%) should be reached through an aggressive fuels development program. The technetium and iodine will be formed separately into fission product targets. Because technetium transmutes to another solid (ruthenium), and because technetium has a large resonance capture cross section (prefers to capture neutrons as they are slowing down), there are no apparent problems in transmuting technetium except the fact there is a great deal of it to be converted. For this reason, the technetium rods are likely to remain in the ATW transmuter for many years and perhaps decades before any processing is needed. Although most (over 80%) over the technetium will reside in separate rods, the technetium produced in the blanket during the transmutation process will likely be retained with the remaining transuranics and thus be recycled into the transmuters as part of the fuel rods. During transmutation, the iodine must be converted to xenon gas, and some of the xenon isotopes may compete with the iodine in capturing neutrons. Therefore, there may be incentive to design these targets with gas plena or other features to vent the xenon. It is even conceivable the iodine may not be in solid target form, and may instead be piped in liquid or gas form through the shielding region (iodine is better transmuted with very slow neutrons). Fortunately, there is far less iodine than technetium to be converted.

The throughput of transuranics is derived directly from the fission heat rate of the transmuters. Therefore, the 1.76 tn per year of transuranics corresponds directly to the amount of fission required for the eight transmuters to generate 6720 MWt (including around 90 MWt of beam power). The technetium and iodine throughput is based on consuming those materials in proportion to transuranic consumption. About 0.33 of the excess fission neutrons must undergo capture for fission product transmutation. Each fission event should produce well over one excess neutron, so this requirement should be easily achievable, and a significantly higher burn rate may be feasible. Although the fuel rods will be regularly unloaded for fission product extraction, technetium and iodine would likely remain for many years.

The power production goal assumes 37% thermal efficiency. Liquid lead bismuth could support higher conversion efficiencies due to its high boiling temperature; however, temperature limits associated with corrosion may limit the operating temperature. This conversion assumption results in 2490 MW electric. The power allocation of 380 MWe covers the accelerator power requirements and an allocation to support the separations processing and balance of plant systems. The net power production of 2110 MWe would be sold via the electric grid, providing a large revenue stream that can be used to cover a significant fraction of the plant capital and operating costs.

After sixty years of operation, nearly all of the transuranics will have been fissioned, most of the technetium will have been converted to stable isotopes of ruthenium, and most of the iodine transmuted to stable isotopes of xenon. Any residual quantities of transuranics, technetium, and iodine would be fed into any ATW plants that remain in operating mode. Eventually, the residual inventories of transuranics, technetium, and iodine from the last ATW unit would be placed into long-lived waste forms and placed into a waste repository. That residual inventory is likely to be on the order of a few hundred kilograms. It might also be burned in a dedicated thermal spectrum device.

4.4 Target/Blanket Design Issues

The reference ATW blanket is based on an Advanced Liquid Metal Reactor (ALMR) developed during the late 1980s and early 1990s. Also known as PRISM, the design work was sponsored by the U.S. DOE, led by General Electric with support from ANL, and was formally reviewed by the Nuclear Regulatory Commission. If the ATW target/blankets are based on sodium-coolant technology, as is currently the assumption, it is likely that a system that resembles PRISM would be nearly optimized regarding systems engineering, safety, and costs. Such a unit is illustrated in Fig. 4-2, which shows the proton beam entering from a bermed accelerator (above grade but with earth piled above the accelerator to provide added shielding) and then being bent downward into the target/blanket vessel. The spallation target module is assumed to be separated from the blanket region so as to keep spallation products from entering the entire blanket cooling system. This feature would also allow different coolants to be used in the spallation target and the blanket regions.

Candidate spallation target modules are illustrated in Fig. 4-3. Both modules would be about 50 cm in diameter and around 3 meters tall. Spallation would take place in the top part of the module, and heat would be given off to the outer coolant in the bottom part of the module. With about 8 MW of heat (about 70% of the beam power becomes heat) to transfer, it is possible heat transfer through the module wall would suffice, but flow channels may also be used to augment the cooling process. The beam entrance window at the top of the module would necessitate routine module replacement, probably once every one to three years. For the sodium coolant reference module, most of the spallation neutrons would be produced in tungsten plates clad in inconel. In addition, the window would be made of inconel. Because of the experience with inconel and tungsten at LANSCE and as part of the Accelerator Production of Tritium the developmental costs for this module would be comparatively modest. However, the other spallation target module would be fundamentally easier and cheaper to manufacture (many such units would be needed during the ATW mission), so the effort to qualify the coolant and materials is justifiable.

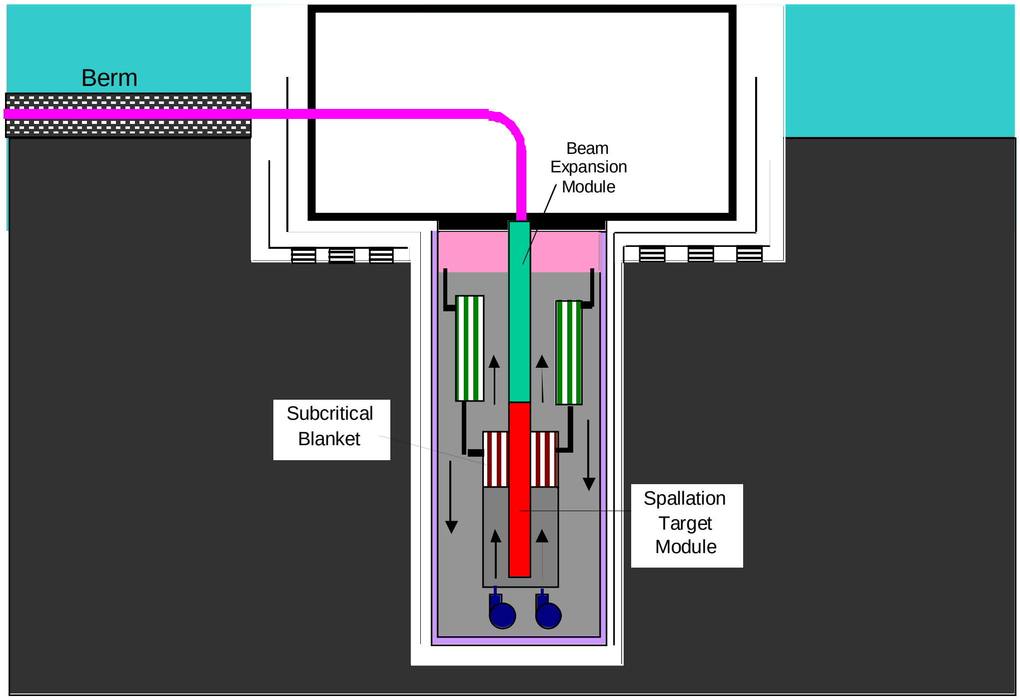


Fig. 4-2. Reference ATW Target/Blanket Configuration

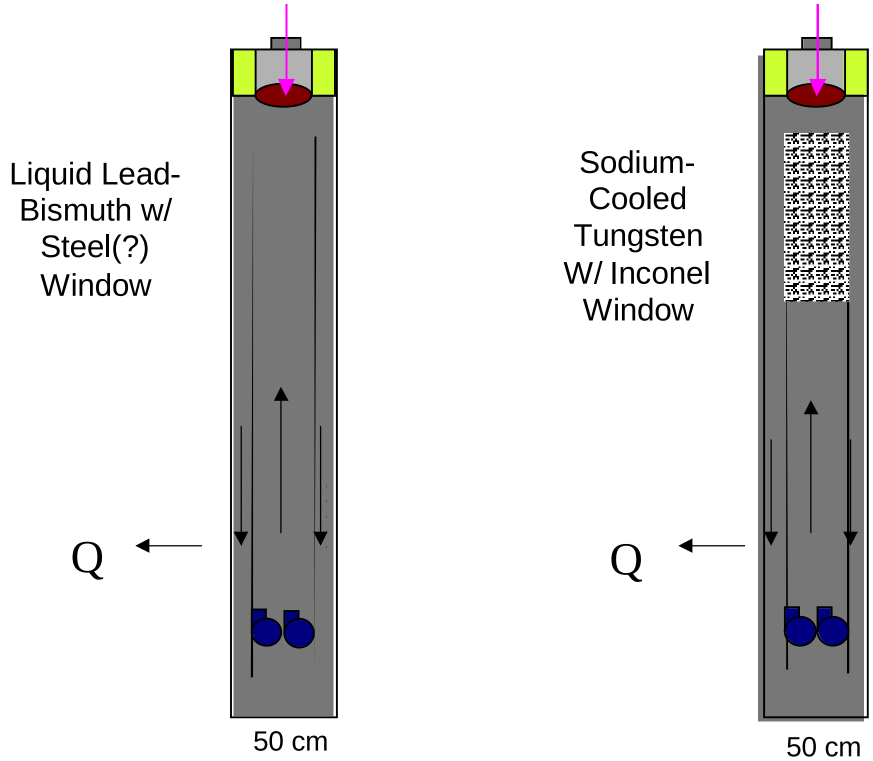


Fig. 4-3. Options for Spallation Target Module

5.0 ATW DEPLOYMENT SCENARIOS

In this section we describe the reference scenario for the U.S., that of no new orders for nuclear power plants, and its effect on deployment of ATW. Major variants to this scenario, which include life extension of existing plants or construction of new capacity to maintain a 100 GWe nuclear in the U.S., are also described.

Finally, scenarios which describe alternate U.S. nuclear futures are discussed. It is concluded that the predominant factor in choosing the size of the ATW plant is the need to dispose of the energy released (as electricity). Different scenarios might lead to differences in fuel form but the fundamental technology choices are unchanged.*

For convenience the ATW development program is assumed to start in 2000, full ATW deployment begins in 2035 with the goal of elimination of the spent fuel by 2110.

5.1 The Reference Scenario

The reference scenario is based upon the current deployment and generation capacity of PWRs and BWRs in the U.S., no construction of additional nuclear power stations, and no license extensions. The implications of this scenario are based on the 1996 evaluation of the nuclear industry in the U.S.,[5-1] with corrections for recent activities including changes in performance and early retirements of nuclear plants. This is an appropriate starting point for this study as it is the scenario referred to by the Energy Information Administration of the Department of Energy in many of their energy projections.[5-2] The calculation of spent fuel production and the transuranics and fission products contained in the spent fuel is described in Appendix A and summarized below.

The current spent fuel inventory in the U.S. is about 40,000 tn. For the Reference Scenario, this inventory is predicted to increase to about 71,000 tn by 2015 and 86,317 tn by 2036, when the license of the last operating plant will expire. The statutory limit for the proposed Yucca Mountain geologic repository is 70,000 tn, although that limit might some day be increased. The inventory of transuranics (TRU) in the 86,317 tn of spent fuel is projected to be about 900 tn with about 90% of that being plutonium. The actual quantity of TRU in 2036 depends on burnup levels and power history of the discharged fuel; for this scenario we used the results of an analysis of historical and projected burnup.[5-2] The average burnup of spent fuel that was discharged during 1998 was about 41 MWt-d/kg, and the cumulative average projection is 37.2 MWe-d/kg by 2036. The spent fuel would contain about 93 tn of the problematic long-lived fission products technetium (73 tn) and iodine (20 tn).

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*International deployment scenarios are discussed in Chapter 9. While their objectives might be different from the U.S.'s, they rely on similar fundamental technical choices.

The energy in the TRU waste, if it could be efficiently utilized, would be sufficient to provide more than twice the current total annual electricity sales in the U.S. (or about 28% of the electricity expected to be produced by U.S. nuclear power through 2036). As a result, reference ATW plants (see Section 4.0) are fairly large, producing a net 2100 MWe of electric power per eight-burner plant (1475 MWe-yr/yr with a projected 70% capacity factor). Even so, an estimated 8.5 plants will be needed to complete the mission (this is a support ratio of about 6.6 LWRs per ATW plant). The scale of this process is not driven by ATW technologies or capabilities, but rather by the amount of energy released during transmutation.

Under this deployment scenario, ATW systems will convert that energy potential to electricity, leaving behind an inventory of about 1000 tn of additional stable or short-lived fission products and less than one tn of the long-lived problem materials. The production of electricity and spent fuel by LWRs and the elimination of spent fuel by ATWs for this basis scenario is illustrated in Fig. 5-1.

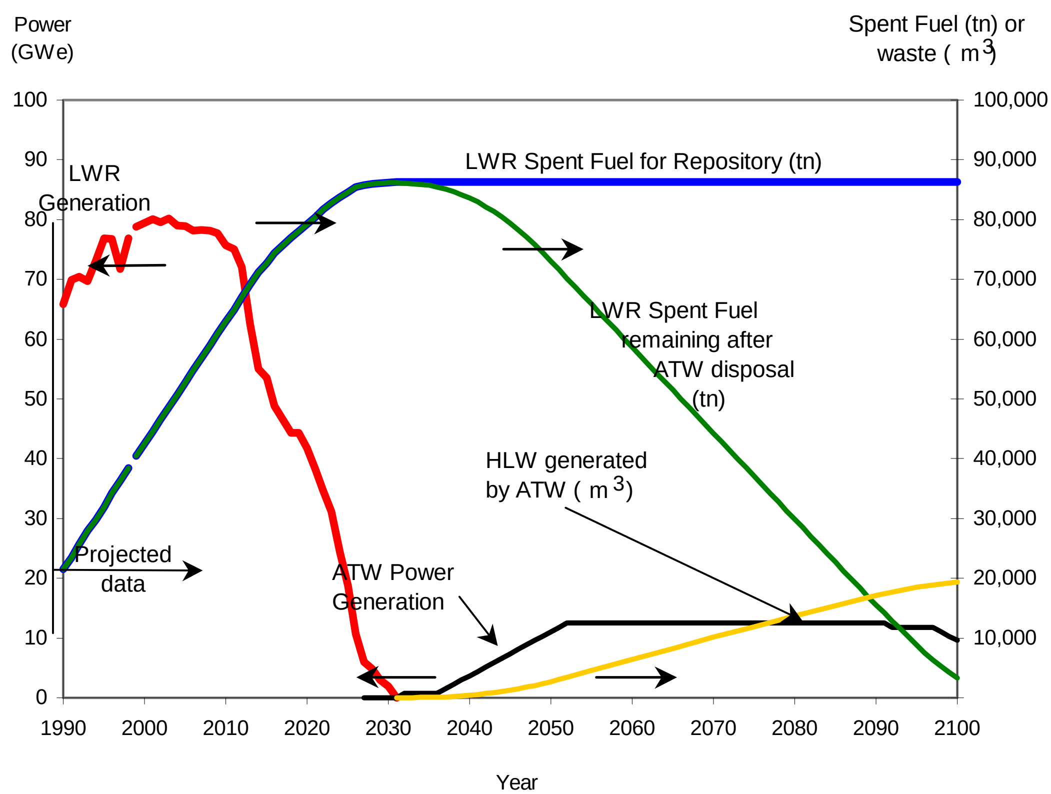


Fig. 5-1. Reference Scenario

The projections are based on energy production and spent fuel generation with existing U.S. nuclear plants, a capacity factor that increases from 78.6% in 1998 to 85% in 2008, and an average burnup at discharge that initially increases then declines at end of reactor lifetimes, with a cumulative U.S. average of 37 MWt-d/kg.

5.2 Limited Nuclear Future

The most plausible alternative scenario of the energy future in the U.S. includes more light-water cooled reactors with a continuation of the existing once-through fuel cycle. To examine a range of potential nuclear power futures, other ATW deployment scenarios were modeled. These included the ATW Reference Scenario (Ref.), also with 20-year license extensions for some plants (Ref.+LE) and a greater average burnup, and a scenario with a continuation of the current 100 GWe of nuclear generating capacity from LWRs. Spent fuel production from these two additional scenarios can be compared with the Reference Scenario by examining Fig. 5-2. Whereas the cumulative spent fuel from the Reference Scenario is 86,300 tn, this production increases in 2050 to 100,000 tn with license extensions and 150,000 tn for the 100-GWe-capacity scenario.

Existing U.S. nuclear power plants generate approximately 2,000 tn of spent fuel per year, and an ATW plant can be expected to process about 10,000 tn of spent fuel during its lifetime. Therefore, a new ATW plant would be built about once every five years to continue to support the existing nuclear generation.

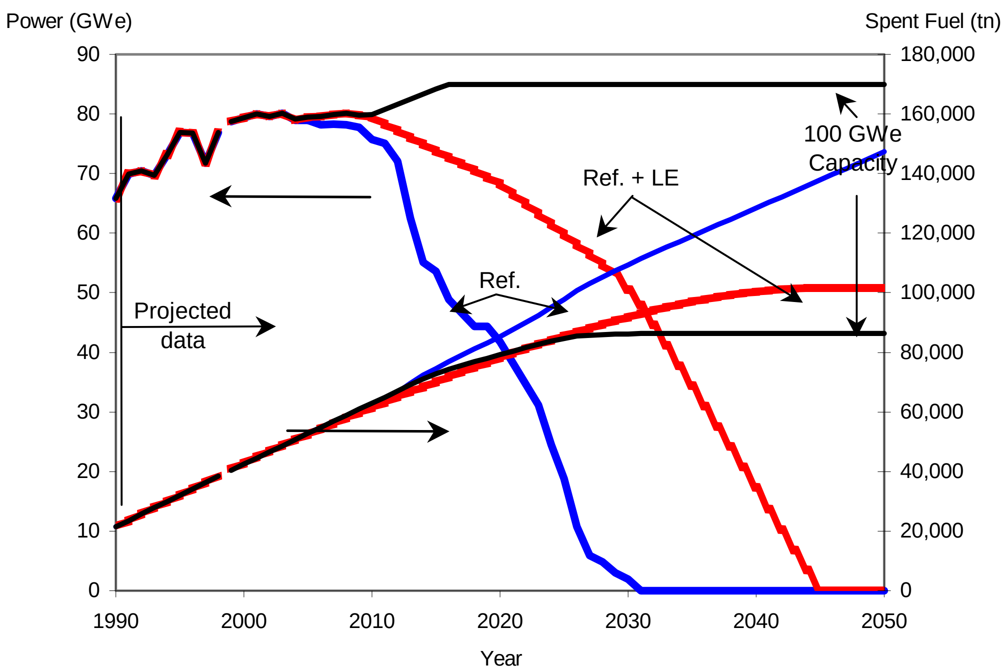


Fig. 5-2. Comparisons of Power and Spent Fuel Production for Three Nuclear Power Scenarios. Ref. = Reference Scenario, Ref. + LE = Reference with 20-year license extensions, and 100 GWe = 100 GWe LWR capacity with an 85% capacity factor by 2008.

The ATW system sized to burn down the legacy of spent fuel will also support a continuation of the current generation of nuclear power reactors. Of course, this may require additional ATW units if only because the plants will age and need replacing.

5.3 Alternate U.S. Nuclear Futures

A future U.S. nuclear industry may be significantly different from that currently envisaged. The MOX fuel cycle is currently constrained by policy in the U.S., but it is feasible and policy can change with new discoveries or new national priorities. Fast reactors have been explored for decades, and prototypes have been built, tested, and operated; it is conceivable that farther in the future, these fuel cycles with their production of fissile materials may become desirable. Projects that were selected recently for funded research and development for the Nuclear Energy Research Initiative include alternate reactors, designs and advanced fuel cycles. In addition, global attention is returning to thorium-uranium fuel cycles, because of the possibility of using increased resources and a potential for reduced proliferation risk. The role of ATW in support of MOX, fast reactors and thorium concepts are described in the following.

5.3.1 A Future with MOX Fuel

The U.S. may choose to burn MOX in light water reactors, as is done in Europe and Japan. This is also similar to one of the "dual paths" of the U.S. weapons disposition program. Fissioning of plutonium in MOX form would reduce the plutonium loading for ATW systems, but the degree of reduction depends on how many passes are made through MOX-fueled reactors and what portion of the total fuel loading includes Pu. Ultimately, the use of MOX fuel leads to a larger discharge of minor actinides per unit power or burnup. If enriched uranium is blended in with MOX, it is possible to transition to an equilibrium in which only minor actinides reach the ATW plants. However, that through-put of minor actinides would more than triple the through-put from the once-through fuel cycle, which will result in an overall increase in support ratio of ATWs of about a factor of 3. Thus, ATW would provide a support ratio of about 20 MOX-fueled LWR reactors per ATW plant (nominal 1000-GWe capacity LWRs per ATW). Even if few Pu recycles are used, followed by transfer of the nth-cycle TRU to ATW systems, the support ratio can increase substantially. For a 4-cycle MOX scenario (3 Pu recycles), the support ratio increases to 12.5 MOX-fueled LWR reactors per ATW plant.

5.3.2 A Future with Fast Reactors

Fast reactors (e.g. liquid-metal fast breeder reactor, LMFBR, and Advanced Liquid-Metal Reactor, ALMR) have inherent advantages regarding consumption of much of their own waste stream and a range of options exists for their implementation. As power producers, fast reactors provide the best performance in terms of utilization of natural resources, with plutonium making up roughly one-quarter of the fuel and uranium making up the balance. In such a mode, fast reactors are capable of providing a nearly endless supply of energy through a process of producing plutonium as quickly as (or more quickly than) it is consumed. In this context, ATW systems could transmute the minor actinides and fission products with a support ratio that is five to ten times greater than the support ratio for light water reactor systems. The support ratio could possibly be between 40 and 80 fast reactors per ATW plant (again, nominal 1000-GWe-capacity fast reactors), so that one or two ATWs could close the back end of this fuel cycle for the current U.S. nuclear generating capacity.

5.3.3 Transition to a Thorium-Based Fuel Cycle

Although the U.S. interest in thorium cycles is currently very localized, there are some interesting advantages to such a fuel cycle. It would reduce the production of plutonium and minor actinides, which would eliminate some troublesome components of the nuclear waste stream. In addition, the cycle can enhance proliferation resistance by spiking the thorium with uranium so that ^{233}U is diluted as it is produced (this is called the DTU, or denatured-thorium-uranium, fuel cycle). In one recent study the support ratio for a DTU-LWR fuel cycle, with recycle of thorium and uranium, was determined to be 14 DTU-fueled LWR reactors per ATW plant. [5-3]

In addition to the technical rationale, the strong advocacy of the Energy Amplifier by the CERN group is sure to draw attention in the U.S. eventually. If the U.S. pursued the Energy Amplifier application, it would result in a large system. The required recycling of plutonium in light water reactors would reduce the plutonium load for ATW, but the dilution of the waste with thorium would increase the scope of the mission significantly. However, the Energy Amplifier is being promoted as an advanced energy system, and if it is economical enough to compete as a power producer, the size of the system may not be crucial for its eventual implementation. Table 5-1 summarizes the support ratios and U.S. requirements for ATW plants with the reference and alternate nuclear energy scenarios.

5.4 ATW System Implementation

An ATW system implementation to addresses the 86,300 tn of spent fuel using the reference plant described in Section 4.3, is illustrated in Fig. 5-3. The first ten to twelve years includes R&D at small scale and at pilot scale. A Spallation Target Facility (STF) is developed at LANSCE, to fit within the existing buildings and site-wide Environmental Impact Statement (EIS). This facility would test the proposed spallation target module (s) and provide a useful source of spallation neutrons for testing ATW candidate fuels and materials.

Concurrent with much of the early R&D and pilot scale work, planning and work to gain approvals for the ATW demonstration facility (Demo) would progress. Because the cost of constructing demonstration scale and full scale accelerators and target/blanket are quite similar, the economics favor building full-scale facilities with partial power capabilities. Therefore, Demo will be constructed with this philosophy. The Demo facilities could be easily upgraded as the technology demonstration effort proceeds.

Construction of an 11 MW accelerator would take place from 2009 through 2013, with the target/blanket construction lagging about two years behind. This is to allow two years of start-up testing on the accelerator, focusing on improving the reliability over conventional accelerators.

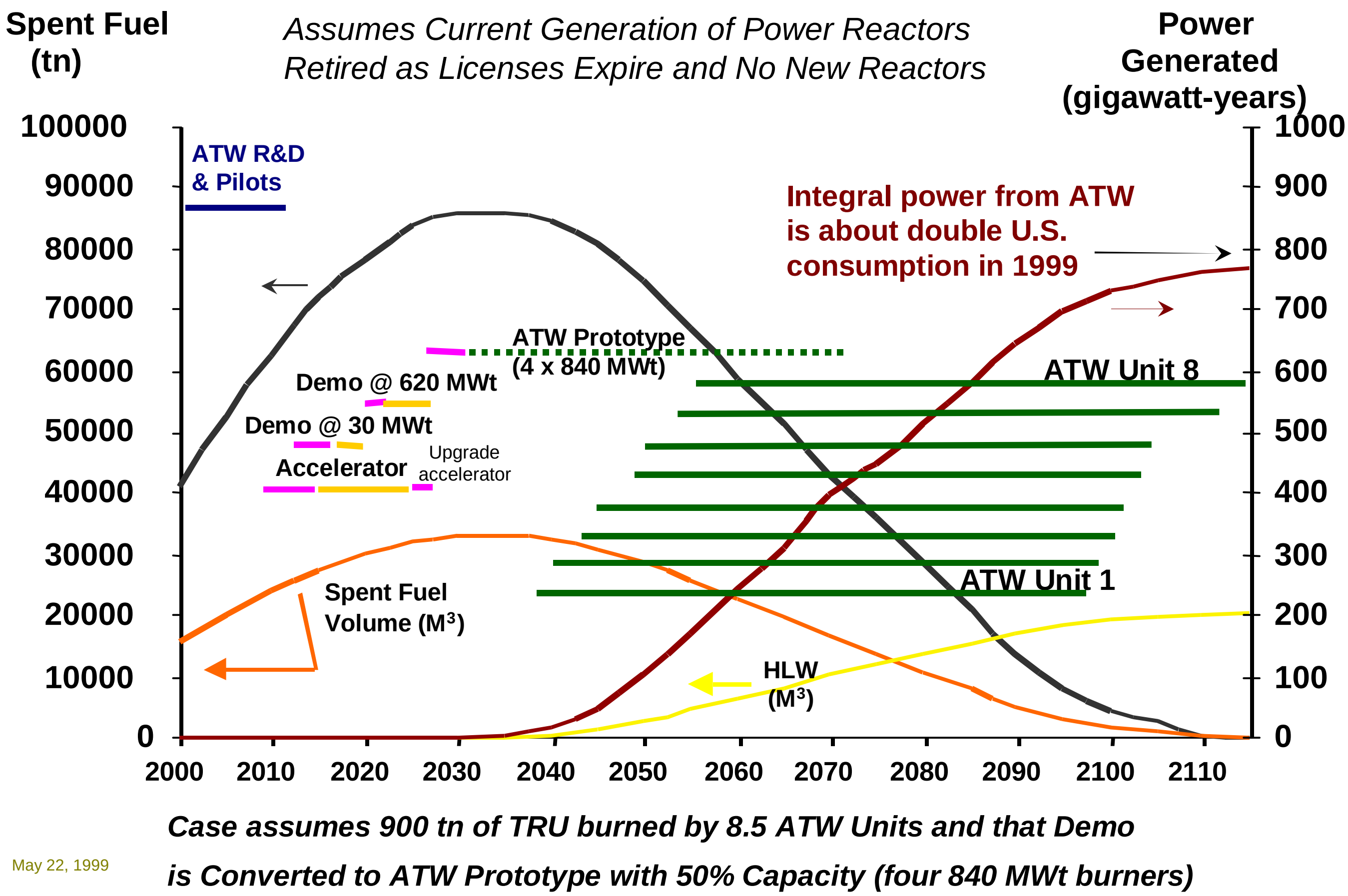


Fig. 5-3. Reference ATW plant implementation to address 86,300 tn of spent fuel

Start-up of a small fuel load (low k_{eff}) would begin in 2015. Periodic upgrading of the fuel loading, the k_{eff} and the fission heat production would lead to a full ATW transmuter loading by the early- to mid-2020's. Successful operation of that transmuter would lead to up to an accelerator upgrade to 45 MW capacity (needs about two years) and construction of three additional target/blankets. At this point (around 2030), the ATW Demo is effectively converted to an ATW power plant and a significant revenue stream is established. Demo will eventually process about 5000 tn of spent fuel.

The full deployment of an eight-unit ATW system could then proceed. Although not shown, it is also likely that pairs of transmuters would come on line in staggered fashion, possibly one per year after the accelerators are up and running.

The time for elimination of the spent fuel inventory, about 75 years, is chosen to make efficient use of the capital investment required to convert the fission energy into electricity. During the period from 2060 until 2095, ATW power plants would be generating nearly 20 GWe, or about 5% of the current rate of total power consumption in the U.S.

Not long after 2100, when the spent fuel has been transmuted, nearly 800 gigawatt years of electric power have been generated from the waste. With respect to total waste volume, the spent fuel reaches a maximum of about 33,000 cubic meters of waste, and the ATW waste residue in the currently assumed customized waste forms occupies about 20,000 cubic meters of "high level waste (HLW)" of a waste repository.

5.5 Summary

The reference scenario for ATW implementation addresses only the spent fuel already generated or that will be generated by existing U.S. power reactors. A resolution of the spent fuel issue may help clear the way for future uses of nuclear energy, and those uses could either increase or decrease the mission for ATW. The ATW concept could be focused on the legacy spent fuel, a different blend of plutonium and minor actinides, solely on minor actinides, or possibly on a transition to a thorium-based fuel cycle. All of these variations are currently being considered in the U.S. and other countries. The reference and alternate nuclear energy scenarios are summarized in Table 5-1, along with associated support ratios and total U.S. requirements for ATW plants. In all cases ATW plants will use the energy from transmutation to produce electricity, which will determine the size of the particular system chosen for implementation. Therefore it is essential that ATW technology be developed in a way that maximizes its flexibility in dealing with different compositions of spent fuel waste and ATW fuel.

Table 5-1. ATW Support Ratios for U.S. Nuclear Generation Scenarios

Scenario	Support Ratio[1] (LWRs per ATW plant)	Number of ATWs Required[2]
Reference, no license extensions (40 GWt-d/tn LWR burnup)	6.6	8.5
Reference with 20-year License Extensions (Ref. + LE)	7.5	10
Level 100 GWe LWR capacity (50 GWt-d/tn LWR burnup)	7.5	13
DTU-fueled LWR and 100 GWe capacity	14	7
1-cycle MOX and 100 GWe LWR capacity	10.7	9
4-cycle MOX and 100 GWe LWR capacity	15	7
Equilibrium MOX and 100 GWe LWR capacity	20	5
Fast Reactors and 100 GWe capacity	40-80	1-2

[1] The Support Ratio is the number of LWRs that each ATW will support. The LWRs are assumed to be 1000-MWe capacity that generate electricity at 85% of peak capacity, while the ATWs are assumed to transmute TRU and generate electricity at 70% of their maximum capacity.

[2] For the Reference Scenario and the Reference with License Extension Scenario, the "Number of ATWs Required" is the minimum number of 8-burner ATWs that will transmute higher actinides from legacy spent fuel. For the other scenarios, the ATWs support a constant (after 2015) 100-GWe capacity operating at 85% capacity factor. In each case, the lifetime of the ATWs is assumed to be 60 years.

References

[5-1] Integrated Data Base Report-1966: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics, DOE/RW-006, Rev. 13, U.S. Department of Energy, Washington DC. (http://www.em.doe.gov/idb97/)

[5-2] U.S. Department of Energy, "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Program," DOE/RW-0510, Washington, DC, December 1998.

[5-3] D. E. Beller, W. C. Sailor, F. Venneri, and J. S. Herring, "A Closed, Proliferation-Resistance Fuel Cycle with Th-U-0_2-Fueled LWRs, Th, U, and Np Recycle, and Accelerator-Driven Transmutation of Waste (ATW)," to be published in *Nuclear Technology*, Proceedings of Global '99: International Conference on Future Nuclear Systems, Nuclear Technology – Bridging the Millennia, Jackson, WY, August 29-September 3, 1999.

6.0 SYSTEM INTEGRATION

6.1 Objective

Three other technical working groups (TWGs) have issued reports [6.1, 6.2, 6.3] where the major technical R&D tasks for the ATW project are defined; they have addressed the areas of target/blanket development, accelerator development, and fuel processing technologies. The TWGs have worked in such a manner as to produce coherent R&D plans. This section describes the integration of these R&D plans into an overall coherent plan, including a definition of the schedule and major milestones, the description of the integration tasks which allow for the project to meet its objectives, a definition of the critical R&D and implementation paths, and the development of an R&D roadmap.

Several points should be noted a priori:

- The reference technology and design parameters defined in this report were chosen without the benefit of detailed engineering, design, and optimization studies. Thus it is deemed essential to launch these types of studies at the initiation of the R&D program. Furthermore, certain concept parameters might be drastically modified by these studies, and this in turn could significantly affect the choice of reference options and the required follow on R&D tasks. A typical example is the choice of fuel composition where the reference design is heavily loaded in zirconium; this might make the pyroprocessing tasks quite difficult, and thus requires an integrated trade study taking into account neutronics, safety, fuels, and processing issues.
- The reference technology was chosen on the basis of an extrapolation of the technical knowledge available in the U.S. Despite many conferences and workshops held during the past several years, a clear and finalized technical international consensus has not yet been developed and no clear international leadership has emerged. To a large extent, the concept of accelerator driven systems is still in a pre-development stage, with no country or organization having committed budgets beyond an initial R&D phase. The international focus on a diverse set of technologies is actually beneficial to the U.S. program, as it keeps open several avenues of research into alternate solutions, and allows the U.S. to concentrate its efforts on driving the chosen reference options towards successful demonstration.
- The R&D schedules developed by the working groups are success driven: they assume that the reference technology chosen for this roadmap exercise as described in section 6.2 will be demonstrated successfully. This assumption is reasonable based on the maturity and implementation status of the chosen technologies. It should nevertheless be noted that several R&D tasks are on the critical path for the overall project feasibility (as described in Section 6.5). While several tasks carry in parallel the development of alternative solutions, these might rely heavily on information from foreign programs and cannot necessarily be implemented without additional confirmatory R&D in the U.S.: thus a setback in any of the elementary tasks on the critical path might have a major impact on the project schedule.

The final objective of this roadmap study must be restated: while the ATW program will have side benefits (such as: development of accelerator technology and of nuclear technologies; production of electricity), it is fundamentally a project aimed at transmuting transuranics and

Long Lived Fission Products (LLFP) in U.S. spent fuel using an accelerator driven fast spectrum subcritical reactor. Technical success of the project will be achieved with a demonstration that the final product of the integrated process (elimination of spent fuel with the generation of various waste streams) can be obtained safely, in a timely manner, at moderate cost, and without increasing proliferation risks; also, these waste forms should be such that their disposal can be done at comparable or lower cost than the disposal of Spent Nuclear Fuel; finally the disposal characteristics of these wastes (i.e. potential toxicity; attractiveness to proliferators) should be a significant improvement from those of SNF. This demonstration will be reached at the end of the R, D&D phase of the project, as described in Section 6.3.

This System Integration Chapter first examines the R, D&D rationale of the project, distinguishes its major phases and states the criteria used to define the R, D&D objectives (Section 6.2)

The development of the R,D&D roadmap and associated costs follows a **deployment driven approach:**

> Section 6.3 reviews the overall R, D & D schedule and its relationship to the major milestones of the project. This relationship defines the programmatic milestones of all phases of the project.
>
> Section 6.4 describes the trade-off, design, and integration studies required for defining the ATW system and for setting quantitative objectives for the R&D tasks.
>
> Section 6.5 reviews the major technical issues which have been identified and need to be solved and summarizes the R, D&D plans which have been developed to address these issues.
>
> Section 6.6 provides the R&D roadmap and the key decision points for the R&D phase of the project.
>
> Section 6.7 provides the R, D&D costs.

Section 6.8 defines a science-based R&D program required for demonstrating key aspects of ATW feasibility, and collecting sufficient information for supporting a decision to build demonstration facilities. This program, presented here independently from the R&D roadmap does not follow a deployment driven schedule but allows for a decision to be taken concerning ATW development after five years, provided sufficient budget is available.

6.2 RD&D Rationale and Criteria

The development plan for the ATW will be articulated around three types of the technologies:

- Reference technologies have been chosen on the basis of the existing U.S. experience: these are the technologies with the minimum amount of development risk associated to them. Use of these technologies reduces the licensing difficulties, the development and implementation times, and the R&D costs. In certain cases (Fuel coolant, spallation target) the chosen reference technologies might provide inferior performance to certain emerging but still unproven technologies: an aggressive R&D program should be undertaken to demonstrate the new technologies; international collaboration in certain non-sensitive areas must be stressed to leverage the U.S. program; collaborations on basic technical and scientific issues will be easy to establish at the inception of the U.S. program and might led to later shared demonstration activities. These reference technologies will provide a technical backup for the case when more advanced technologies cannot be implemented.

- Preferred technologies have been identified, which may provide superior performance provided a large scale R&D plan is completed successfully. These technologies have been chosen from either foreign technologies or ongoing U.S. R&D programs. It should be noted that for certain technologies no backup or alternate option has been identified: these are the cases when the preferred technologies have already reached a good level of maturity with superior performance and their adaptations to the ATW program are expected to be feasible. Failure of their development plans, while unlikely, would force the ATW to rely on foreign technologies currently under development. The preferred technologies are in certain cases similar to the technologies pursued by foreign programs. A typical case is the lead Bismuth Eutectic coolant. In these cases aggressive international collaborations should be pursued to reduce the cost of the R&D program, increase the probability of success, and possibly also reduce the duration of the program.
- Alternate technologies have been identified which would be implemented in case reference/backup or preferred technologies do not meet project requirements (due to technical or institutional issues). In general, the ATW project should not invest significant amounts of efforts in these technologies, and will rely on exchange of information with foreign organizations. The framework for these exchanges still needs to be established. It might rely on existing international forums such as the regular OECD activities. Alternate technologies have been identified in Chapter 3, and Appendix B.

Table 6-1 identifies the reference and preferred technologies.

The implementation of this dual approach calls for building successive facilities with the reference technologies, until successful completion of the preferred R&D paths. At these times, decisions will be taken by the project to either continue reliance on the baseline technologies, or switch to the preferred technology. The cost and schedule impact of such switches have not yet been assessed.

The development plan for the ATW comprises the following four phases:

- A **preliminary investigative phase**, where the available technologies are assessed and simplified system concepts are assembled from the most promising technologies. This task has been initiated and partially completed by LANL with internal funds.
- A **system integration phase**, which defines the system performance requirements, runs trade studies, followed by detailed design studies, and defines optimized reference parameters and R&D needs in view of performance and licensing requirements. This task has not yet been started.

Technology	Preferred Technology	Experience for Preferred Technology	Reference/ Backup Technology*	Experience for Reference/Backup Technology	Alternate Technologies
Fuel coolant	LBE	No U.S. experience. 30 years of proprietary Russian experience. Several reactors built and operated. R&D programs are being initiated in Europe and Asia.	Sodium	40 years of U.S. and open international programs. Several reactors built and operated.	Helium
Spallation target	LBE	None	Tungsten	APT program	None
Spent LWR nuclear fuel treatment	Aqueous process	30 years of U.S. and international program. Several plants built and operated.	Aqueous process	30 years of U.S. and international program. Several plants built and operated.	Pyrochemistry
Fuel form	Metallic	IFR Program	Metallic	IFR Program	Nitride
ATW fuel treatment	Pyrochemistry	IFR Program	Pyrochemistry	IFR Program	None
Accelerator	Linac	IFR Program	Linac	IFR Program	None

*The reference/backup technologies are used for costing purposes only. They will serve as backup should the R&D for the preferred technologies fail.

Table 6-1. Reference and preferred technologies for ATW

- A **R&D phase** which is aimed at first evaluating the feasibility of the reference and preferred technical options, and then continues during the demonstration stage of the program to provide data for improving the system performance. This R&D program also initially collects the existing information on the chosen technologies and sets the operating conditions of the first phase of the demonstration task. The R&D program concentrates on the technological elements which are novel in the ATW project: lead-bismuth technology investigated in parallel with a minimal sodium technology program, coupling of a spallation source to a subcritical system, core and system control, fuel fabrication and performance, aqueous treatment and pyrochemical separation for the LWR SNF, pyrometallurgical treatment of a new fuel form, extrapolation of accelerator size and performance, system safety, and development of technologies for eliminating long lived Fission Products. The program will have a strong emphasis on the preferred technologies and will have a moderate emphasis on the reference/backup technologies; minimal work will be performed for the alternate technologies. Small scale facilities will make maximum use of existing infrastructure to support the R&D objectives:

    - A spallation test facility will be built at the site of the LANSCE accelerator to test the spallation characteristics of the lead bismuth eutectic and of the tungsten target. There is a strong potential for international collaboration in this area.
    - A small LBE loop will be built to validate the Russian database and technologies. There is a strong potential for international collaboration in this area.
    - Benchtop experiments will be run to demonstrate the feasibility and performance of the fuel processing technologies.
    - Fuel fabrication and sample irradiation experiments will be run in existing facilities.
    - Neutronics experiments will be conducted in collaboration with foreign organizations in existing facilities.

- A **demonstration phase** where successive sets of facilities are built or upgraded with increasing levels of system optimization and increasing sizes. The first small scale demonstration phase consists of constructing (possibly within existing complexes) pilot facilities for the front and back end fuel treatment. These facilities are used to demonstrate the concept feasibility, confirm the reference options, gain operating experience, and collect data for supporting the licensing of the following phases. The front end fuel treatment pilot facility will also be used to provide the fuel for the startup of the accelerator driven subcritical system . Experiments will also be run to collect sufficient data to extrapolate operating conditions. The second large scale demonstration phase consists of constructing a set of demonstration facilities comprising an upgradeable accelerator, full scale front end and back end processing facilities, and an upgradeable subcritical target with operating conditions close to expected final nominal conditions. These facilities will be built on a government site and will be used to demonstrate the performance of the concept including the waste burning rate and waste form performance. Experiments will be run to allow for optimization of the design. The prototype phase will consist of building a set of facilities centered on a full size subcritical target, full size accelerator and full size fuel processing facilities. These facilities will be used to demonstrate the feasibility of a full-scale system and will provide data for further system optimization and deployment. R, D&D is completed at the end of this phase.

The above phases are described in detail in Section 6.3.

6.3 RD&D Schedule and Major Milestones

This section describes the R, D&D schedule, including the integration phase, the R&D phase, and the demonstration phase.

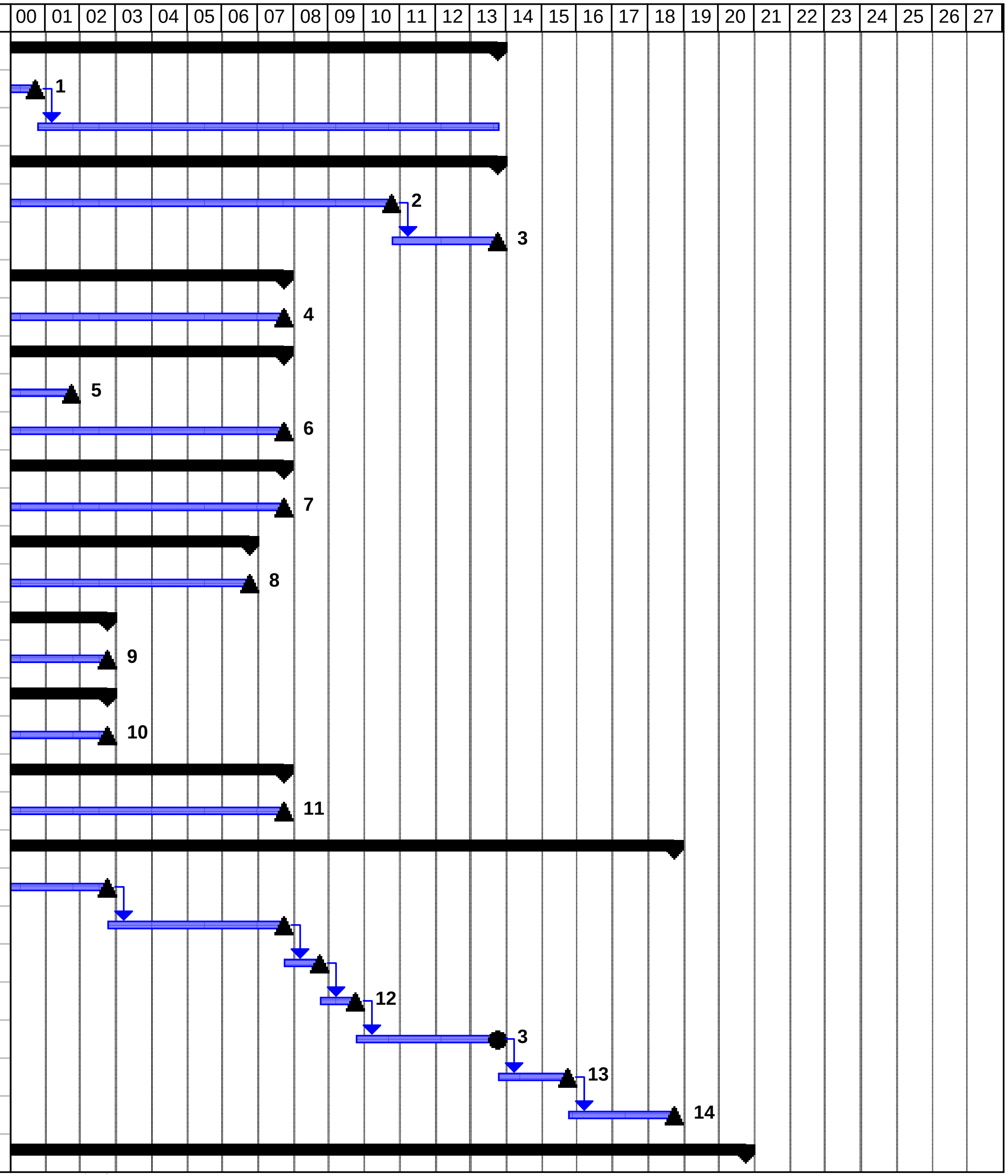
The overall ATW implementation schedule is described in Appendix D. This schedule was developed with the objective of an early and aggressive ATW deployment. This criterion constraints all phases of the development plan, in particular the R&D schedule and conditions the annual cost of the R&D tasks.

The major technology development milestones and their effect on R&D requirements are related to the startup of a Demonstration Plant in 2016 and are described in Figure 6-1. This startup date strongly conditions the completion of the R&D tasks (fuels, core physics, system safety, target accelerator, coolant and separation processes). The following describes the key activities required to obtain a full demonstration of the ATW technologies.

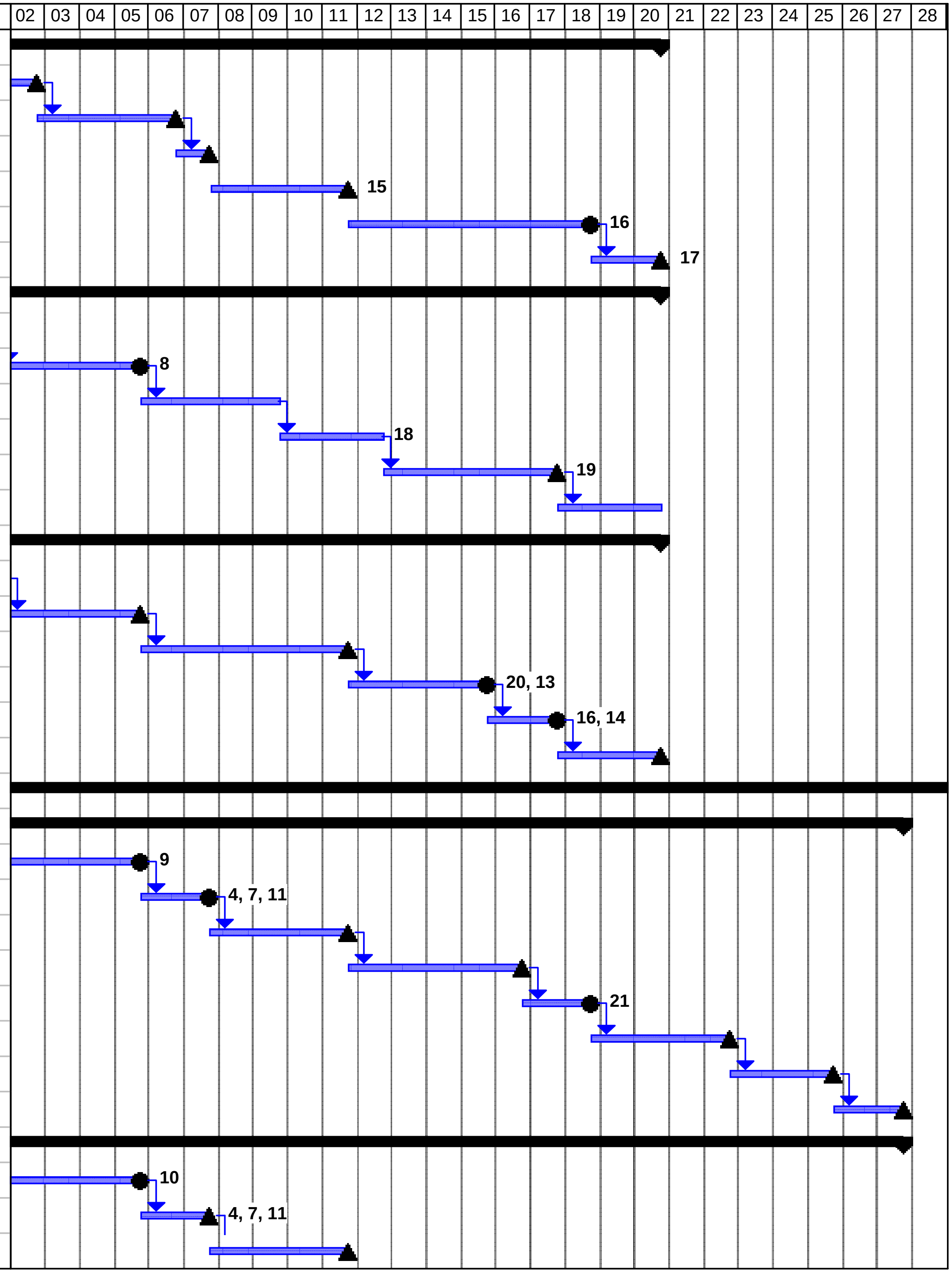
- **Trade Studies and System Integration Phase**

Reference options, performance requirements, design choices, and design parameters have been chosen for the road mapping work without the benefit of trade studies, design studies or optimization studies. Thus it is clear that the system used for developing the RD&D program and associated cost needs to be significantly reviewed before launching pre-conceptual work. A series of multi-disciplinary trade studies are required to address the following parameters: system performance (actinide and fission product burning and separation rate; overall reliability; efficiency of electricity production; waste form performance); system size (size of accelerator; size of individual burner unit); system deployment rate; choice of technical concept (comparison of various subcritical concepts); choice of technologies (e.g., coolant and fuel types; target design; system control); choice of technical parameters (e.g., fuel composition, maximum fuel

ID	Task Name
1	**Trade Studies**
2	Definition of major options
3	Optimization
4	**Fuels R&D**
5	Fabrication; basic properties; irradiation behaviour (prelim)
6	Fabrication; basic properties; irradiation behaviour (final)
7	**Core Physics R&D**
8	Validated Codes and Core Design Studies
9	**Safety R&D**
10	Definition of safety strategy
11	Safety tools and analyses
12	**Target R&D**
13	Target concept; window material
14	**Accelerator R&D**
15	Compactness, reliability
16	**Front End Separation R&D**
17	Process demonstration
18	**ATW Separation R&D**
19	Process demonstration
20	**Coolant Technology R&D**
21	Coolant Technology R&D
22	**Pilot Front and Facility**
23	Conceptual Design
24	Design and Construction
25	Cold Ops
26	Hot Ops
27	Production
28	Test Fuel
29	Production for 420 MW Load
30	**Pilot ATW Demonstration**



ID	Task Name
1	**Pilot ATW Demonstration**
2	Conceptual Design
3	Design and Construction
4	Cold Test
5	Hot Ops
6	Lag
7	Recycle Operations
8	**Fuel-Scale Accelerator**
9	Conceptual Design
10	Title I Design
11	Title II Design
12	Construction
13	Startup Tests
14	Operations
15	**Demo Burner**
16	Pre- and Conceptual Design
17	Title I Design
18	Title II Design
19	Construction
20	30 MW Operations
21	420 MW Operations
22	**FTF**
23	**Proto Front-End Plant**
24	Pre- and Conceptual Design
25	Title I
26	Title II
27	Construction
28	Test
29	First Proto Fuel Load
30	Operations for Proto and Succesors
31	Operations with Proto Fuel
32	**Proto ATW Processing**
33	Pre- and Conceptual Design
34	Title I
35	Title II



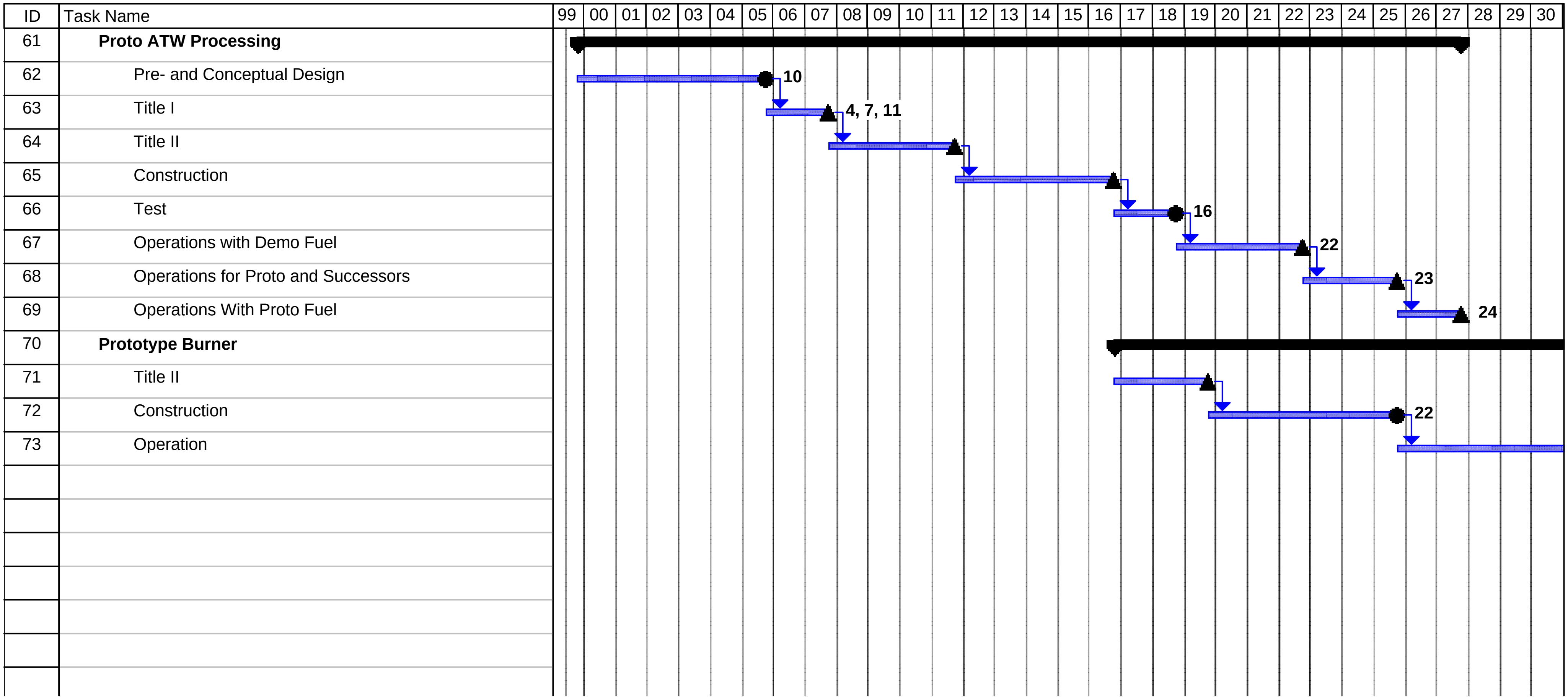


Fig. 6-1. Reference Demonstration Path (Contd.)

burnup, core reactivity level, etc.). The definition of the system performance requirements strongly conditions the content of the R&D programs.

Milestone (1): all initial trade studies (described in detail in Section 6.4) needed to define the system design choices, options, and R&D needs, must reach preliminary conclusion after one year.

Trade studies will continue after this milestone, and will incorporate feedback from the R&D program, from foreign R&D programs, and from facility operations. They will also account for potential changes in institutional criteria.

- **Basic R&D Phase**

The objective of the R&D is to collect sufficient information on all R&D technologies to allow for the licensing, design, and construction of the demonstration facilities.

Milestone (2): fuel fabrication tasks must be completed within 11 years in order to provide data for Title II design of the FTF (Fuels and Target Facility).

Milestone (3): fuels properties and behavior tests must be completed within 13 years in order to provide data for the final Safety Analysis of the Demonstration burner operating at 420 MWth with the ATW fuel form. These data comprise:

- fuel mechanical properties
- fuel thermodynamic properties
- fuel/clad/coolant compatibility demonstration
- fuel irradiation behavior

Milestone (4): the core physics R&D task will provide a complete set of validated codes to the design team of the Demo facility after 8 years. It will also provide better understanding of core control issues, design tradeoffs, dynamic behavior, burnup reactivity compensation, isotopic evolution, and LLFP incineration concepts.

Milestone (5): the safety R&D program will define a safety approach to the ATW and licensing requirements within 2 years.

Milestone (6): the safety R&D program will develop the safety tools and analyses required for Title II design of the demonstration plant after 8 years.

Milestone (7): the target R&D task will provide a demonstrated target concept, including a choice of window material and its properties, to the design teams of the Demo burner and accelerator after 8 years.

Milestone (8): the accelerator R&D task will provide solutions for reducing the accelerator size (use of superconducting technologies) and for improving the accelerator reliability to the accelerator design team after 7 years.

Milestones (9) and (10): the separations R&D tasks will conduct a series of analytical studies and bench top experiments to confirm the basic processes used for element partitioning after 3 years.

Milestone (11): the R&D tasks required to demonstrate the coolant technology need to be confirmed after 8 years.

Note that all R&D tasks will be continued at a reduced level after completion of the milestones. Feedback from other R&D programs and from facility operations will be used to optimize the processes.

- **Demonstration Phase**

The objective of the demonstration phase is to build and operate facilities to demonstrate the feasibility and performance of the ATW technologies at pre-prototypical scale.

Fuel Processing Pilot Facilities

Two pilot facilities will be built to demonstrate the processes at small scale, and provide fuel to the first burner.

The Pilot Front End Facility will start partitioning commercial Spent Nuclear Fuel in 2009. The reference process will be established in 2010 and the corresponding data made available for FTF (Fuel and LLFP Transmutation Assembly Facility) Title II design (Milestone 12). The facility will then be used to produce test reference fuel assemblies for irradiation in the demonstration burner (Milestone 13) and a partial or full load of reference fuel for the upgrade of the demonstration burner to 420 MW (Milestone 14).

The Pilot ATW Processing Facility will start partitioning reference irradiated ATW fuel (or some form of a representative reconstituted fuel) in 2008 (note that the origin of that fuel is still unclear. The reference process will be established in 2011 and the corresponding data made available for FTF Title II design (Milestone 15). This facility will be used at a later date, in 2019, when irradiated ATW fuel becomes available from the demonstration burner (Milestone

16). Recycle operations will proceed for three years and will result in a demonstration of the ATW waste forms (Milestone 17).

Demonstration Accelerator

The demonstration accelerator will be constructed by 2013 (Milestone 18). Three years of startup tests will be used to improve the accelerator reliability, until nominal operations start (Milestone 19).

Demonstration Burner

The first fuel load (U-Zr fuel with a few ATW test assemblies) will occur in 2016, at which time the burner will operate at 30MWth (Milestone 19). After three years of operations, irradiated test assemblies will be sent to the Pilot ATW Processing Facility and to the FTF (Milestone 16) and the facility will be upgraded to 420MWth with fuel fabricated in the Pilot Front End Facility.

Prototype Fuel and LLFP Transmutation Assemblies Facility

The front end section of the FTF will become operational in 2019 (Milestone 21) and will produce the first load of fuel for the prototype burner in 2023 (Milestone 22).

The back end section of the FTF will become operational in 2019 (Milestone 23), will operate with irradiated fuel from the demonstration burner and until 2026, when the first batch of irradiated ATW fuel will be discharged from the prototype burner (Milestone 24). This milestone constitutes a crucial demonstration point in the ATW project, as it corresponds to the production of the first prototypical waste forms, and the first burner operation with recycled fuel. It completes the technical demonstration of the ATW project.

After 2027, FTF and the prototype burner will continue operation to reach an equilibrium mode, and will also be used to optimize the various processes.

6.4 ATW Trade Studies and System Integration Phase

As has been noted earlier, the reference design of the ATW system used in the road mapping exercise has not benefited from extensive design and optimization studies. Thus it should be considered only as a benchmark for defining preliminary R&D plans and associated costs. A major task of the ATW project at its inception will be to carry out a series of trade studies preliminary to launching design activities. A "top-down" approach will be used to investigate the ATW technical options, choose the most promising options, set performance objectives, and provide quantified goals for the R&D plan. The studies will successively concentrate on the following aspects:

- definition of system performance objective
- definition of system size, layout, and deployment rate
- choice of ATW system
- choice of ATW technologies
- choice of technical parameters
- analysis of institutional issues related to development and implementation

6.4.1 System Performance Objective

In the process of partitioning and transmuting Spent Nuclear Fuel the ATW system produces waste forms which must be disposed of, and energy which can be converted into electricity and sold to offset a significant fraction of the cost of deploying and operating the system. The goal of this task is to set performance objectives for these functions.

Separated Uranium is a waste product obtained from partitioning the SNF. The preliminary criterion imposed on this waste form is that it can be disposed of as non-TRU class C waste. This implies a very high recovery rate of the TRU and fission products, and requires the use of a demonstrated aqueous process, or the potentially costly development of a pyrochemical process. Trade studies are required to evaluate the advantages and disadvantages of producing a lower purity waste form: while the disposal of lower purity uranium would be more difficult, it could be produced with a non-aqueous process which could gain easier public and institutional acceptance.

High level waste forms are produced by the pyrochemical separation of TRU and Fission Products, and from the extraction of Tc and I from the Fission Product stream. Because of the importance of the TRU elements to non-proliferation objectives and to repository performance, a very high recovery rate for TRU will be required. Trade studies are required to optimize this recovery rate taking into account on the one hand the advantages to the repository, but also on the other hand the increased R&D and operational costs of a more complex process.

Two material streams pass through the ATW "system": a metallic TRU fuel form and fission product (FP) transmutation assemblies. The fuel form composition (TRU and Zr content) has not yet been finalized and requires a specific trade study to define it. A higher TRU content would ease the pyrochemical requirements, but might degrade the irradiation and neutronics performance; a lower cycle burnup would reduce the burnup swing and associated control requirement, but would require more fuel recycling steps and thus increase the losses to the waste stream. The FP irradiation targets require considerable development; preliminary trade studies are needed to decide whether once through targets are feasible or whether recycling steps will be required. Several concepts have appeared in the literature and need to be compared and studied.

Electric power production, while not the primary objective of the ATW, will be used to offset the deployment and operations costs. The revenue generated from electricity sales will strongly depend on the system thermodynamic efficiency and on the system reliability and load factor. Thermodynamic efficiency can be raised by increasing the system operating temperature. On the other hand, this would decrease the mechanical resistance of structural materials and, particularly in the case of LBE coolant, might have significant effects on the corrosion control procedure. Trade studies will be performed to decide the optimal reactor operating conditions, taking into account 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 incineration and electricity production) is directly dependent on the system load factor; furthermore the sale price of electricity depends strongly on the reliability of the system. Thus, there is a strong incentive to increase the system reliability. Reliability of the standard nuclear system has been well mastered in the past and can be brought to a high level; nevertheless, the reliability of existing accelerators to provide uninterrupted operation requires substantial improvements for TW as it is recognize that even relatively short accelerator shutdowns will entail lengthy reactor restart operations. While an aggressive accelerator R&D program is planned, preliminary trade studies are necessary to evaluate global 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 will be used to set the R&D objectives of the various programs.

6.4.2 System Size, Architecture, and Deployment Rate

The reference plant architecture devised for the ATW Roadmap comprises two 45 MW proton linear accelerators feeding eight 840 MWth transmuters, with one chemical processing plant servicing these eight transmuters. This layout was obtained on the basis of various past studies, for example APT system-level-analyses which showed that a single large accelerator is much less costly than several smaller accelerators producing the same total beam power, and ALMR studies which favor modular, passively safe, 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 transportation of 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 aims at burning all U.S. SNF in a relatively short time (75 years). The relevance of this objective must be assessed. In particular trade-offs between the system costs, associated risks, and expected benefits must be reviewed.

6.4.3 Choice of Technical Concepts

Various concepts similar to ATW have been proposed in recent years, which are aimed at transmuting Spent Nuclear Fuel. They can be classified according to fundamental properties such as: spectrum (fast and thermal), fuel type (solid, liquid), coolant (LBE, lead, sodium, gas), etc., see Section 3.

While most international programs seem to be evolving towards fast-spectrum-liquid-metal-cooled subcritical assemblies driven by large linear accelerators, a variety of other concepts retain attractive features and are being investigated internationally.

We propose that the U.S., should investigate the merits and drawbacks of a number of proposed systems before launching into an extensive R, D&D program. In addition, a technical comparison of the relative performance of accelerator-driven and critical reactors systems should be undertaken. These studies will be performed during the first two years of the program.

6.4.4 Choice of Technologies

Within the framework of the reference technical concept chosen in the previous studies, several global technical options remain undecided which might have significant effects on the proposed R&D program.

In order to achieve optimal burning rates and energy production, each transmuter unit should operate constantly at nominal power. This 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 burnup throughout 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; it also has direct consequences on the safety behavior of the system. Several approaches can also be considered for using the accelerator beam as control mechanism. For example, beam power adjustment to individual burners may be practical using multiple low-energy linacs to inject separate beams into the main accelerator, and/or using variable beam splitting arrangements. These technologies, while requiring specific R&D efforts, might offer some advantages for controlling the global ATW system. Specific studies should be planned to devise an optimized system control strategy.

The safety strategy and licensing requirements for the ATW need to be established rapidly to allow for the licensing of the demonstration facilities. This requires that a number of preliminary safety studies be run in order to establish a safety basis and modify the plant concept in order to mitigate potential off-nominal events and their consequences. It should be noted that while there is a significant safety basis already established through the Advanced Liquid Metal Reactor program, the safety behavior of the ATW will be significantly modified due to the use of an accelerator driver (and potentially due to the use of LBE coolant). APT safety studies have provided an additional framework, particularly with respect to the accelerator drive and fast beam abort systems.

A major technological choice of the ATW program will be between LBE-cooled, LBE-target designs, and Na-cooled, solid target designs. Both approaches have advantages and drawbacks that have been widely discussed. It is not believed that trade studies will be sufficient to make a final choice. Rather, an extensive R&D program and some form of international consensus will be required. Nevertheless, initial trade studies should be run to clearly define the comparative technical, safety, and cost implications of both options and thus establish objectives for the LBE R&D program.

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

6.4.5 Choice of Technical Parameters

Several technical parameters need to be set in order to develop R&D plans which will permit the chosen technologies to meet the objective system performance. They are here classified by basic technical fields, even though it is recognized that strong links exist between these fields.

6.4.5.1 SNF Treatment and Pyrochemistry

The purity levels of the waste stream have already been identified as a major performance parameters. Furthermore studies will be needed to investigate the trade-off between the waste volume and the waste 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.

6.4.5.2 Fuel Development

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

6.4.5.3 Blanket Development

Preliminary trade studies will be needed for defining both basic and design aspects of the blanket development program. The basic aspects will 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 blanket (e.g., fuel form, LBE coolant, spallation source) render existing analysis codes in need of enhancement and establishes a requirement for fundamental data. The preliminary studies will 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 global system characteristics. The major parameters are:

- The blanket multiplication factor which when raised reduces the accelerator power requirements, but might also decrease the safety margins and operational flexibility of the system.
- The fuel composition, burnup rate, and management strategies.
- The blanket control strategy.
- The degree to which natural convection participates in the pumping requirements needs to be investigated, taking into account specific design approaches and safety consequences.
- The operating temperature of the blanket.
- The neutronic feasibility of various designs for LLFP transmutation assemblies needs to be investigated, taking into account achievable burning rates, recycling and treatment performances, and safety consequences.

6.4.5.4 Spallation Target Development

Early design studies will need to 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, transient behavior).

6.4.5.5 Accelerator Development

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

- Integration of the accelerator design in the global control strategy;
- Development and analysis of strawman accelerator designs, including cryomodule architecture, RF system architecture, cryosystem concept, beam-sharing and control, and beam-transport architectures for ATW plants;

- Analysis 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 assuring redundancy, invulnerability to component failures, and rapid recovery from faults;
- Fabrication and manufacturing strategies to reduce costs and improve component performance.

6.4.6 Institutional Analysis

Institutional challenges for the development and implementation of an ATW 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 a period of many decades.
- Public acceptance issues arise with respect to both the overall policy commitment to implement ATW and to the siting and operation of the required facilities.
- Regulatory/NEPA issues arise with respect to the regulatory requirements for ATW activities, the regulatory requirements for a high-level waste repository (which will provide a basis for the performance requirements of the ATW system), and NEPA requirements for development and implementation of an ATW system.

Previous studies concluded that “a tightly managed development program” would be required to develop and demonstrate the technologies required for any separations and transmutation system. This is certainly true of the RD&D program for development of an ATW system. Successful implementation of this program requires coordination and integration of the activities of multiple participants and multiple DOE sites over an extended period of time. Experience in other complex projects supports the development of a mission-oriented single-purpose organization that could implement a program extending over a period of decades.

The proposed ATW research, development and demonstration program would require continuous funding over a multi-year period. Successful international collaboration and industrial partnerships also depend upon confidence that the federal government’s participation in such efforts will be sustained. Absent a credible commitment to sustain support for an ATW development program over an extended period, it might be difficult to obtain substantial commitments from international or industrial partners to participate in collaborative ventures involving significant costs and risks.

It is questionable if the Nuclear Waste Fund could be used for development of separation and transmutation technology under current provisions of law. Public utility commissions views might be a significant consideration if use of the Waste Fund for development of an ATW system were allowable under the law. The NWPA imposes the Nuclear Waste Fee on nuclear utilities; however, public utility commissions must approve the pass-through of the costs to the utilities' ratepayers. Some public utility commissions might question such a pass-through of expenditures for ATW RD&D unless it is clear that ATW is necessary to enable waste disposal to go forward. The institutional analysis should review potential organizational and management alternatives and develop a strategy for the development and demonstration phase.

Implementation of a full-scale ATW system would certainly be subject to the same type of regulatory requirements as other parts of the nuclear fuel cycle. In order to ensure that a demonstration facility demonstrates not only the technical and financial but also the regulatory feasibility of ATW, the regulatory requirements need to be defined clearly and the facility should be designed and constructed as if it were subject to those requirements.

The existing regulatory structure of the nuclear fuel cycle needs to be reviewed to insure applicability to all parts of the ATW. Current NRC regulations relate to nuclear reactors not designed or used primarily for the formation of plutonium or ^{233}U. This suggests that some addition or revision to current regulations might be required to cover an accelerator-driven transmutation device. The appropriate regulatory structure would need to be developed before a full-scale system could be designed. The institutional analysis should address these issues and present a regulatory compliance strategy for the demonstration and implementation phases.

Experience with both the WIPP and Yucca Mountain projects shows that conducting a scientific development program under rigorous QA requirements can be a significant challenge. This experience, particularly the experience of the Yucca Mountain project in dealing with NRC QA requirements, should be examined carefully for applicability to an ATW RD&D program.

An ATW system will require a programmatic environmental impact statement covering activities through the construction and operation of a demonstration facility. This document should be developed along with the pre-conceptual design and present the various programmatic alternatives for transmutation of spent fuel, and the impacts associated with each. The programmatic environmental impact statement should be one of the primary vehicles to engage the public and work toward public acceptance of the ATW system.

In addition to regulatory requirements for its own facilities, the ATW system must have a clear performance objective as a basis for its design and operation. Near-total destruction of all of the radionuclides of concern is likely to be neither feasible nor necessary. Decisions must be made about how much reduction is required for which radionuclides.

Development, deployment, and operation of an ATW system for treatment of the projected inventory of spent fuel will face institutional challenges that are similar in kind to those facing development and operation of a high-level waste disposal system. Studies of the institutional aspects of high-level radioactive waste management concluded that the institutional challenges should be considered as important as the technical challenges. In keeping with this conclusion, the technical development of the ATW system should be accompanied by institutional analysis to develop recommended approaches for dealing with them.

Section 7 contains a full discussion of these issues.

6.5 Major Technical Issues and Associated R&D Program

This section provides an overview of the major technical issues which have been identified during the ATW roadmapping exercise, and briefly summarizes the R&D plans which will address these issues. Note that major issues are defined as those which might evolve into showstoppers if left unresolved.

The issues are classified by broad categories: system-wide issues, and issues relevant to each technical area (accelerator development, separation process development, and target-blanket development).

6.5.1 System-wide Technical Issues

Two major issues have been identified which are relevant to the global system design:

- System sizing: in the reference path used for this roadmap, it was assumed that the burners would have the power and size of a PRISM module, that one accelerator would serve four burners, and that one Fuel Target Facility would serve eight burners. Trade studies will need to be run to optimize these parameters.
- System control: the control of the basic system (one accelerator, four burners) can rely on adjusting several elementary parameters: accelerator power, beam sharing between burners, control rods, burnable poisons. The control problems are significantly more complex than for a standard fast reactor, due to the presence of the accelerator and also due to the large burnup swing expected in the system. Furthermore, safety criteria and a global safety strategy have not yet been fully developed. System control has been identified as an R&D task in the blanket/target program, and also as a subject of the necessary trade studies.
- System safety: The safety approach for the ATW has not yet been fully defined. It is likely that safety scenarios not related to criticality will be similar for ATW and standard reactor designs. Nevertheless, a fundamentally new approach has to be devised for criticality and accelerator related scenarios and adequate licensing requirements need to be developed.

6.5.2 Accelerator Development

One major technical issue has been identified relevant to accelerator development: it concerns accelerator reliability. In the past development of accelerators, reliability had systematically received a lower priority than system protection. Nevertheless, when the accelerator is coupled to a sub-critical system, its reliability becomes of prime importance to the system performance: even a very short accelerator trip can trigger thermal shocks in the reactor component and might also imply a lengthy reactor restart. Two tasks have been identified:

- System studies will be run to quantify the reliability requirements for the accelerator, taking into account consequences on the reactor integrity and global system performance.
- An extensive R&D program is planned to identify the root causes of accelerator trips, and correct them in time for the design of the first ATW accelerator.

Accelerator controllability might also need to be investigated, if trade studies demonstrate its desirability.

6.5.3 Blanket/Spallation Target Development

Six major technical issues have been identified relevant to the blanket spallation/target development:

- Subcriticality control has already been mentioned in regards to global system control. The control problem is made difficult by the expected large burnup swing, and the lack of finalized safety criteria. An R&D plan has been devised to consider several options: use of control rods and burnable poisons, use of movable fuel and reflector assemblies, design of a low burnup swing core reload and shuffling strategy.
- Safety strategy: the subcriticality of accelerator driven systems is believed to offer an important safety advantage over critical systems in that the former are able to accommodate unprotected reactivity insertion accidents when fertile-free fuels (with low Doppler feedback and small delayed neutron fraction) are employed. On the other hand, accidental increases of the source are possible in accelerator driven systems, and thus the ability of ATW system to safely accommodate various source transients must be demonstrated. In addition, the weaker sensitivity of accelerator driven systems to reactivity feedback effects, makes these mechanisms ineffective in reducing power, making the shutdown of the neutron source essential to preventing system damage under such accident conditions. The potential for fuel melting due to under-cooling and for subsequent accumulation of fuel into a critical mass is particularly serious in view of the low Doppler co-efficient, small delayed neutron fraction and (for LBE coolant) the high inertial resistance of the heavy liquid metal to fuel dispersal. A similar safety concern arises from the potential of attaining supercriticality through seismically induced compaction of the core. These safety issues, as well as safety issues

unique to the use of LBE coolant and to the containment aspects of coupling of an accelerator and a subcritical reactor. Thus, a new safety strategy needs to be developed; a series of trade studies will be required to refine this strategy and optimize the system design accordingly; existing analysis tools might need to be updated.

- Fuels performance: while the ATW fuel has some similarity with the IFR fuel form, new challenges appear due to its high Zirconium content, high minor actinide content, and high target burnup. Trade studies which involve fuels, separation, and core physics aspects are planned to define the optimal fuel composition and target burnup. The fuels development plan addresses the issues of fabricability, compatibility, and irradiation performance through a series of specific tests.
- Transmutation target design and performance: specific targets will need to be used for the transmutation of the Long Lived Fission Products. The international R&D programs in this area are still in their infancy, with limited demonstrations available. A vigorous R&D program is planned to assess the design, fabricability, and irradiation performance of these targets.
- The target window material is subjected to high intensity exposure to charged and neutral particles, and to large thermal stresses. Design and materials R&D programs are planned to understand the irradiation behavior of the window and optimize its design.
- The LBE technology has been essentially developed in Russia and remains proprietary. Licensing criteria will be developed for the U.S. program, and the technology will be transferred and verified through a quality assurance program and a series of confirmatory tests.

6.5.4 Separations Technologies

Three major technical issues have been identified relevant to the separation technologies:

- The feasibility of pyroprocessing as a treatment option for the spent commercial fuel needs to be evaluated. Difficulties are related to the scale up in size required from present benchtop processes and to the purity requirements used for this roadmapping. Trade studies will be run to assess the possibility of relaxing the purity requirements. An extensive R&D plan will aim at developing and demonstrating the process.
- The performance of the pyroprocessing of ATW fuel needs to be established. Difficulties arise from the large fraction of Zirconium in the fuel, and from the significant amount of Americium. Specific process development and demonstration tasks are planned.
- The performance of the final waste forms with respect to radionuclide retention over long periods of time in geological repositories will be established.

6.6 R&D Roadmap

A roadmap has been developed for the initial investigative and R&D phases of ATW. Note that this roadmap does account for later activities, stemming from feedback from operating facilities, by allowing for improving the performance of the options developed during the R&D phase.

Fig. 6-2 summarizes the R&D roadmap for the ATW.

Element 1: System integration

The system integration task coordinates the project management and the R&D programs. In particular, it organizes the trade studies which have been identified in Section 6.4.1, and defines after the first year of effort, system criteria and R&D requirements.

This task also provides the framework for international collaboration and monitors the development of alternate concepts and technical options in international programs.

Quantified goals for the R&D tasks will be set by element 1 after one year.

Element 2: Accelerator development

The accelerator development R&D program has two components:

- Compactness: the objective is to design a more compact accelerator. It will rely on superconducting technologies. Design studies and experimental demonstrations are planned. This component will be terminated at the time of the demonstration accelerator design freeze.
- Reliability improvement: the causes for accelerator trips will be identified and studied. Technological improvements will be designed and assessed experimentally. While the design of the demonstration accelerator will be frozen in 2005, this task will continue, and provide input for potential upgrades or modifications.

Another important aspect, accelerator controllability will be developed within Element 8, Core design and system control.

Element 3: Fuel form development

The R&D task will be concentrated on the base technology (metal fuel); its objective is to demonstrate fabricability, compatibility, and irradiation performance by 2008. No alternative will be studied; nevertheless, foreign programs will be monitored. A decision point occurs in 2008: if the baseline R&D program is successful, that technology will be adopted for system design, and R&D task will continue for improving the fuel performance; failure of the R&D task

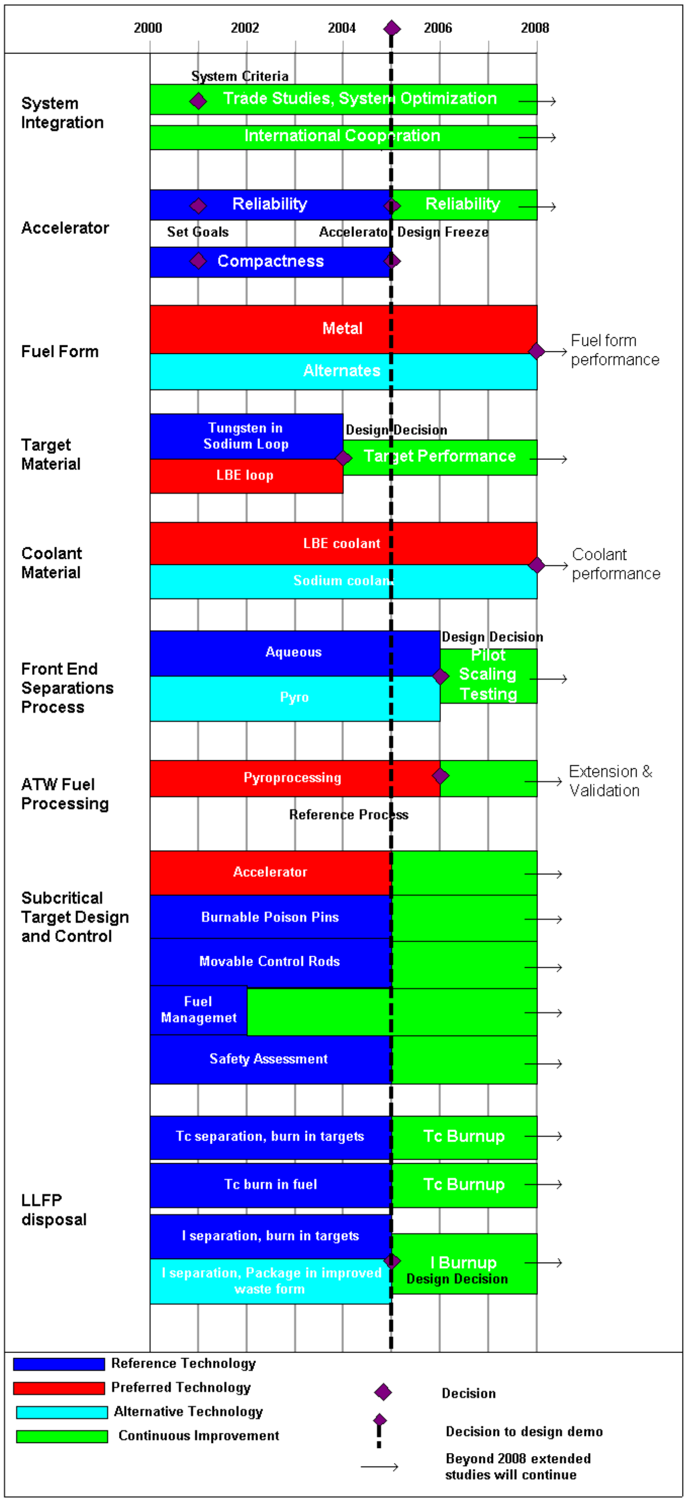


Fig. 6-2. R&D Roadmap

would imply a major setback for the ATW program: alternate foreign fuels would need to be adopted: this would postpone the R&D and deployment planning by several years, and would also have a major impact on the separations task.

Element 4: Target material

Two R&D tasks will be run in parallel for the first four years:

- The characteristics of solid tungsten targets in sodium coolant will be assessed. The tasks will include: spallation characteristics, irradiation performance, window material development, and engineering design of the target.
- The characteristics of a LBE target in a separate loop will be assessed. The tasks will include: spallation characteristics, technology transfer and QA of Russian data, confirmatory test of material corrosion characteristics and of chemistry monitoring technology, window material development, and engineering design of the target.

A decision point between these two options is set for 2004. After that time R&D efforts will be concentrated on improving and optimizing the chosen option.

Element 5: Fuel coolant material

Two R&D tasks will be run in parallel for eight years.

- For the sodium coolant, a small R&D program will be needed to confirm existing data until the demonstration burner design is frozen in 2008.
- For the LBE coolant the R&D program will be aimed at transferring the Russian LBE technology and confirming it. Irradiations of the reference fuel form in a LBE environment will be required. Data will be collected to provide the basis for design and licensing in 2008.

Element 6: Front end separations process

Two parallel R&D paths will be pursued until reaching a decision point in 2008:

- A R&D path for the aqueous process, will be concentrating on flowsheet development and analysis, and on the recovery rate of the LLFP's.
- A R&D path for the pyroprocess will concentrate on improving the Uranium stream purity, and on scaling up the process.

Element 7: ATW fuel processing

A unique technology is considered for the processing of the ATW fuel. The first three years of R&D will be aimed at establishing the reference processes. The follow on R&D program will be aimed at demonstrating, improving, and optimizing the process.

Element 8: Core design and system control

Two major tasks are required for this element:

- A R&D path to design an optimal core configuration and fuel management strategy (along with the fuel composition and maximum burnup). This task will result in a preliminary conceptual core design in 2002. Activities would be continued thereafter to obtain an optimized final core design by 2008.
- A second path to study and demonstrate technologies for system control: the baseline technologies will be burnable poisons and control rods. The use of accelerator intensity control will also be studied. A decision point is scheduled for 2005.

Element 9: System safety

Two major tasks are required for this element.

- A R&D path to identify safety issues and establish a safety approach for resolving them for ATW, should produce a preliminary definition after two years and will be optimized thereafter.
- An implementation path to develop the required tools, perform analyses to resolve safety issues and ensure a high level of safety, and design the system accordingly.

This activity will establish a safety basis for ATW after five years.

Element 10: LLFP disposal

Two baseline approaches will be studied and implemented for Tc disposal: homogeneous (Tc in fuel) and heterogeneous (Tc targets) technologies. The R&D task will study the performance of these two approaches, and implement the tests needed for demonstrating the Tc separation capability, the target and fuel fabrication, and the expected burning rates. A conceptual design of the two approaches will be available in 2006.

The baseline technology for iodine separation is the heterogeneous (target) approach. The R&D task will evaluate concepts, study their performance, and implement the tests needed for demonstrating the Iodine separation capability, the target fabrication, and the expected burning rates and recycle requirements. A conceptual design for this approach will be available in 2006.

An alternate approach for Iodine disposal will be considered: namely its disposal in an improved waste form.

6.7 RD&D Cost Estimate

Costs estimated for an accelerator transmutation of waste research, development and demonstration (RD&D) program is about $10B, distributed among program elements as indicated in Table 6-2.

Table 6-2, RD&D Cost Summary

Program Element	**R&D Cost ($B)**	**Demonstration Cost ($B)**	**Total RD&D Cost ($B)**
Accelerator	0.16	2.20	2.36
Target-Blanket	1.03	1.99	3.02
Separations	0.50	1.90	2.40
Integration	0.08	0.87	0.95
Fuel Fabrication	N/A	0.55	0.55
Site support	N/A	0.98	0.98
Retrieval, Transport And Disposal	N/A	0.11	0.11
TOTAL	**1.77**	**8.60**	**10.37**

Annual cost by program element is illustrated in Figure 6-3, *Annual RD&D Costs*.

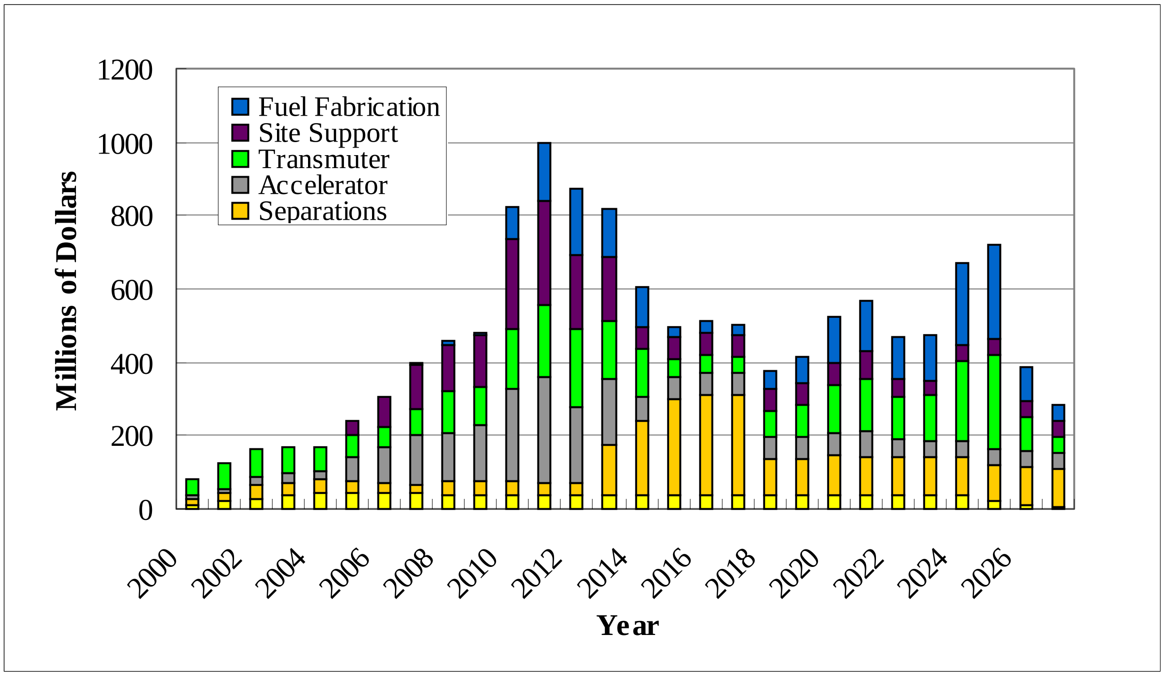


Fig. 6-3. Annual RD&D Costs

Each program element somewhat autonomously performs research whose costs are readily estimated and understood on an element-by-element basis. Research and development (R&D) costs have been separated from demonstration costs and R&D costs are discussed by individual program element in Sections 6.6.2 through 6.6.5. However, demonstration of an ATW system is accomplished in one integrated facility and, although the costs of a demonstration facility can be segregated by program element, the demonstration facility is better understood when discussed as a whole. The integrated costs of a demonstration facility are described in Section 6.6.1.

6.7.1 Demonstration Facility Cost Estimate

The accelerator demonstration is designed to create a machine that can serve multiple purposes, by providing the test bed for developing, testing, and demonstrating the operational reliability capability and the high beam current capability required of a ATW system accelerator, and by then serving as the ATW accelerator for the first sub-critical reactors at the first ATW station. Thus, the demonstration accelerator must be built on the site of the first station, and the station support infrastructure (balance of plant) for that station must also be built and placed in service at the same time to support the accelerator demonstration. The balance of plant comprised all of those functions, both physical and administrative, needed to support station operations. The physical portion includes such things as basic process and potable water supplies, waste water treatment systems, station electrical distribution switchyards, including the large switchyard for distribution of the power produced by the ATW power blocks, roads, sidewalks, railroads, fire protection, emergency response and first aid facilities, station physical security (fencing and electronic surveillance) and security and accountability for the special nuclear materials that will be processed and used at the station. The administrative function includes the personnel to staff the various support functions listed above, and the general business staff and management necessary for such a station to function. For the current cost estimate, it was postulated that the full station support facilities were put in place during the construction period and all were fully staffed by the time (2014) the accelerator demonstration unit was placed in service. Total demonstration costs are listed in Table 6-3.

Table 6-3. Demonstration Cost Summary

Program Element	**Demonstration Cost ($B)**
Accelerator	2.20
Target/Blanket Burner	1.99
Separations	1.90
Integration	0.87
Fuel Fabrication	0.55
Site Support	0.98
Retrieval, Transport and Disposal	0.11
Total	**8.60**

The demonstration period for the accelerator is postulated to begin in 2014, operating at an initial low beam current of about 0.4 mA, but capable of increasing to an 11 mA beam current. The beam is directed to the demonstration ATW sub-critical reactor in 2015 to provide the source for initial testing at power levels from 30 MWt to 450 MWt through 2021 and for more testing on accelerator reliability. During this period, electricity to power the accelerator (and the rest of the station) must be purchased, at a cost of about $11M/yr for the accelerator, resulting in an operating cost of about $77M/yr. The accelerator is then upgraded during 2021 and 2022 to yield a 45 mA beam current, and that beam is again directed to the demonstration sub-critical reactor which is now configured to produce the design power level of 840 MWt. The turbine-generator set for the first power block is placed into service during the accelerator upgrade period, and subsequently produces sufficient electricity to power the accelerator, thereby reducing annual operating costs for the demonstration accelerator by about $41M/yr, to about $43M/yr. The accelerator and the sub-critical reactor continue to operate in the demonstration mode, examining the effects of accelerator/sub-critical reactor/turbine-generator interactions, through 2027 which is designated as the end of the demonstration period. Annual ATW demonstration costs are illustrated in Figure 6-4.

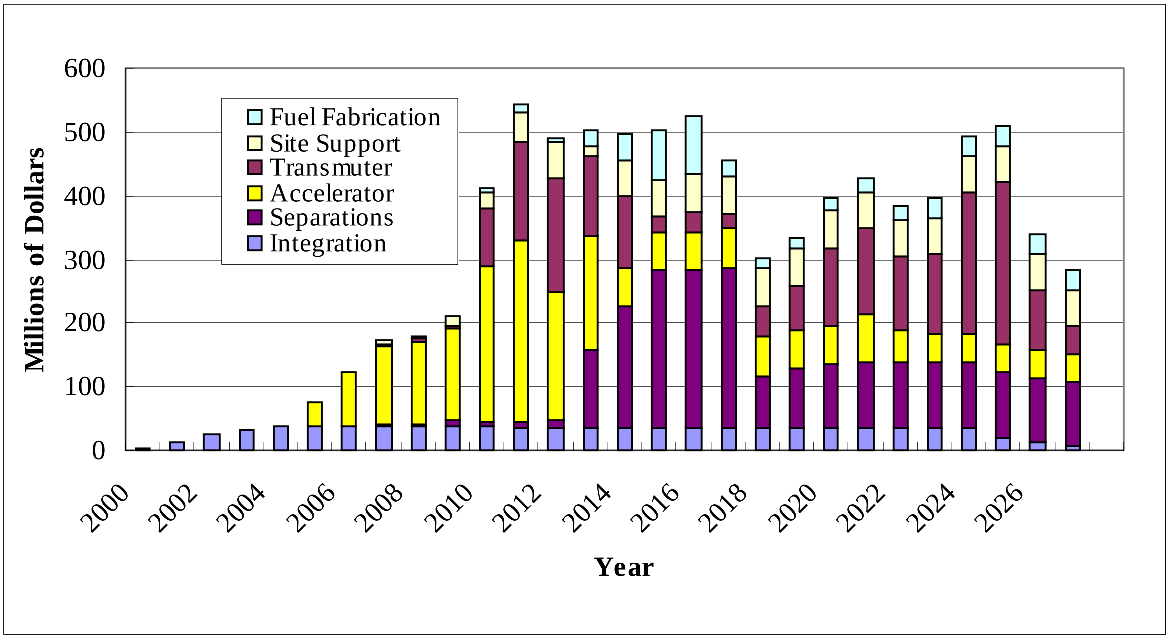


Fig. 6-4. ATW Demonstration Costs

While the demonstrations for the accelerator and sub-critical reactor are going on, the facilities for the demonstrations of the LWR SNF processing, ATW processing, and ATW fuel fabrication are designed, constructed, and placed in service. These facilities are constructed full-sized, i.e., with sufficient space to accommodate the additional equipment needed to bring the facilities up to full production rate during the demonstration phase. ATW fuel for the initial testing and demonstration activities in the sub-critical reactor is produced in existing hot cell facilities at national laboratories. The subsequent ATW fuel needed to bring the sub-critical reactor from the 30 MWt to the 420 MWt power levels, and the fuel needed to load for 840 MWt operation is produced in the station fuel fabrication plant, with source material produced by the station LWR processing plant, both working in the demonstration mode. As irradiated ATW fuel assemblies become available, either from an off-site test program or from on-site operations, they will be processed through the ATW processing plant for recycle into ATW reload fuel assemblies for the station. These activities will continue through 2027, the end of the designated demonstration period.

6.7.2 <u>Accelerator R&D Costs</u>

The ATW accelerator technology development activities' costs were estimated based on experience with similar activities for the relatively mature Accelerator Production of Tritium (APT) Program. Further, the ATW program will build upon, and not duplicate, recently completed research activities in APT that are directly transferable to ATW. Thus, ATW will recover a significant portion of the government research investment in the APT program. Two research and development (R&D) activities which were not included in APT but are critical to the success of ATW are accelerator beam reliability and beam controls for chopping and splitting the beam between burners. These two activities that are unique to this accelerator application compromise the largest fraction of ATW accelerator technology development costs. The complete accelerator technology development program is discussed in detail in the separate *Accelerator Technical Working Group Report* [6-2].

The total ATW accelerator R&D costs for the first 7-8 fiscal years are expected to be about $165M. For accelerator research, major cost elements are the procurement of components and the cost of operations to test components on an operating research accelerator. ATW linear accelerator (linac) components and radio frequency (RF) components are accounted for separately in Table 6.4. The test bed for ATW component testing is expected to be the Low Energy Demonstration Accelerator (LEDA), and LEDA operations cost were estimated on the basis of operations experience at the Los Alamos Nuclear Science Center (LANSCE) linear accelerator. Capital costs for LEDA are assumed to have been born by the APT program.

Table 6-4. Accelerator R&D Cost Estimate

R&D Task	**Estimated Cost ($M)**
LEDA Operations	38
LINAC Components	47
RF Components	33
Splitters Development	16
Reliability Improvement	32
Total Estimated R&D Cost	**165**

In existing high-power accelerators such as the LANSCE linac, the beam is interrupted typically about once per hour, due to RF-station faults, injector faults, or other equipment outage. Most of these interrupts are very short duration (less than one minute), which would not have caused a problem in a system designed for accelerator production of tritium. However, the penalty for frequent short-term beam interrupts in an ATW system is severe, both in terms of transient response of the burners, and also the impact on the electric power grid. A major objective of the ATW accelerator R&D program will be to understand the causes of beam interrupts in high-power linacs, and to reduce their frequency to very low values. This kind of "micro-reliability" is a new requirement for accelerator design and operation, and has not previously had much emphasis. The development program to address this issue would require construction and long-term testing of representative high-reliability versions of RF power stations, injector, and other key components of an ATW linac. This program would lead to equipment installed in the demonstration linac that has an extremely low fault rate, in comparison with current experience.

Operation of the demonstration facility itself provides a long term evaluation of these designs and an integrated testbed for further improvements.

Since the demonstration accelerator will only need a relatively modest maximum beam current in its initial operation (11.25 mA), there is no urgent need to develop higher power RF components during the FY00 – FY07 R&D phase. However, in the demonstration facility upgrade, which occurs in 2021-2022, it would be desirable to refit the machine with components that demonstrate the ATW prototype plant operation to maximum advantage. It is likely that higher power RF components will be desired in this phase, with klystron and RF-chain power levels going up to about 2.5 MW from the currently available 1.0 MW. Development programs pushing in this direction should begin in the 2000-2007 period, and become mature well before 2021.

Design for lower-cost manufacturing is a long-term effort that should also be started in the early R&D period, and continued beyond the first implementation phase of the demonstration linac. There are potentially large cost savings to be obtained in the deployment of the ATW plant linacs by a strong and sustained effort in this area. This program is a combination of design and manufacturing prototyping, with the objective of developing fabrication methods for components employed in large quantities in a high-power accelerator (such as SC cavities, klystrons, power supplies, circulators, RF windows, vacuum elements, magnets, etc.) that are significantly less costly than current approaches.

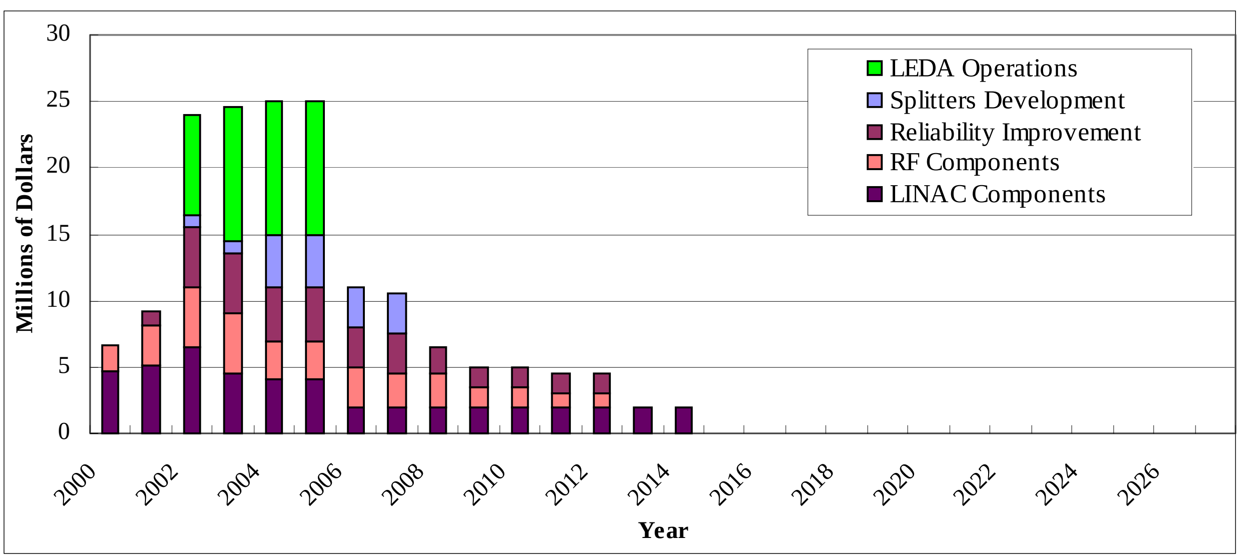


Fig. 6-5. Accelerator R&D

The annual distribution of accelerator R&D costs are illustrated in Fig. 6-5.

6.7.3 Target-Blanket R&D Costs

Many of the Target-Blanket research activity costs are based on estimates for similar research activities that had been planned for the advanced liquid metal reactor (ALMR) program, with the costs normalized to CY1999 dollars. Government and private sector organizations have extensively reviewed ALMR cost estimates. Target-Blanket research activities unique to ATW were estimated using activity based cost accounting techniques. Total research and development cost for the target-blanket program element is estimated to be about $1B.

Table 6-5. Target/Blanket R&D Cost Summary

R&D Task	R&D Cost Estimate ($M)
Target Technology	30
Blanket Technology	188
LBE Coolant Technology	166
Sodium Coolant Technology	492
Nuclear Design & Safety	154
Total	**1030**

Sodium and Lead-Bismuth Eutectic (LBE) are the primary coolants considered for fast neutron spectrum operations. Sodium and LBE coolants each offer distinct advantages and drawbacks, so a careful assessment will be required to select the optimal choice. To apply sodium reactor technology to an accelerator driven system, development activities should include the design and testing of a sodium-cooled solid target, the materials issues with operating in the proton beam, and the effect of the proton beam on sodium chemistry. It is expected that the basic technology required will be substantially similar to that developed for the ALMR program, and can be adapted to the ATW concept with minimal modifications.

The integration of nuclear coolant, spallation target and reflector using the same fluid in the ATW LBE target concept drastically simplifies the subcritical burner design by streamlining flow configuration and by removing target and reflector structures. 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) and have recently proposed extending the technology to pure lead systems. Recently, considerable insight was gained in the Russian implementation of the LBE technology, which is also favored in Europe and Japan for ATW-like applications and generated interest in the U.S. for use in future "proliferation-resistant" reactors. In view of the large potential benefit to the implementation of the ATW concept, we are of the opinion that a strong technology transfer effort should be pursued in the ATW R&D phase to fully master this technology.

Research and development activities for target technology, blanket technology, and nuclear design and safety proceed in parallel with the dual-track coolant research until a coolant design decision is made in 2008. Two major target technologies are being researched: a solid tungsten target cooled by liquid sodium, and a lead-bismuth liquid target that may be integral to, or separate from, the coolant system. Two major blanket technologies are being researched: dispersion fuel (primary candidate) and cast fuel (backup technology). Nuclear design and safety activities influence all other target-blanket research.

It is assumed that an accelerator, whose costs were previously described, provides the protons necessary for target-blanket research and development. The complete target-blanket technology research and development program is discussed in detail in the separate *Target-Blanket Technical Working Group Report* [6-3]. Annual target-blanket R&D costs are illustrated in Fig. 6-6.

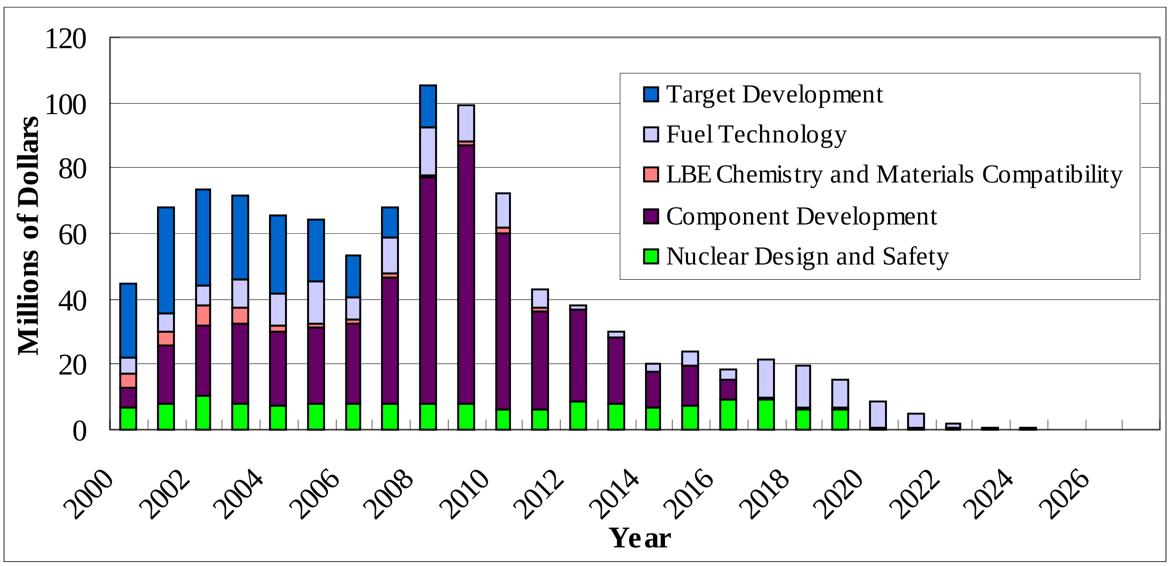


Fig. 6-6. Target/Blanket R&D Costs

6.7.4 <u>Separations R&D Costs</u>

Separations technology development activities include the R&D necessary to assure the technical performance of the individual processes proposed at a scale sufficient to support 8 transmuters operating at a single location. Because of extensive U.S. experience in aqueous separations and pyroprocessing, there is a high level of confidence is the activity based accounting estimates for these processes. The complete separations technology development program is discussed in detail in the separate *Separations and Waste Form Technical Working Group Report* [6-1].

Table 6-6. Separations RD&D Cost Summary	
R&D Activity	**R&D Cost Estimate ($M)**
Waste Forms	87
ATW Fuel Processing	230
LWR Fuel Treatment	182
Total	**499**

Total cost (Table 6-6) for the separations and waste form R&D activities is about $0.5B. The costs are heavily weighted in the early years (Fig. 6-7) because research/pilot scale facilities are designed to be sufficient to support target-blanket testing and demonstration facilities' initial fuel load.

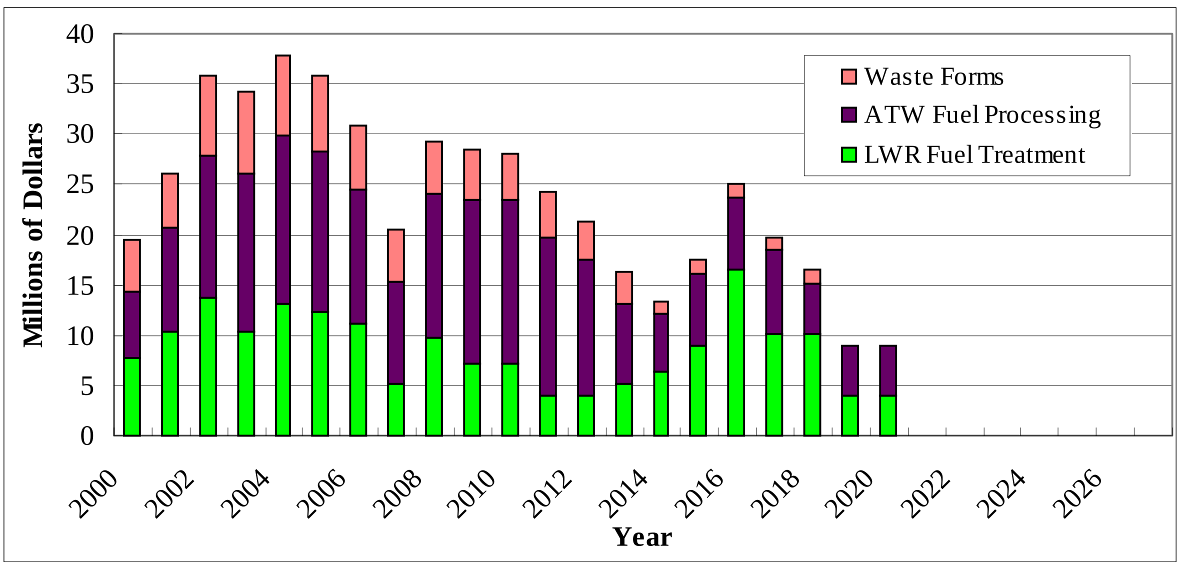


Fig. 6-7. Separations R&D

Three major research activities are performed in the separations program element: LWR fuel treatment, ATW irradiated fuel processing, and waste forms. LWR fuel treatment extracts from LWR spent fuel (1) the TRU elements (as metals) for use in the fabrication of ATW fuel, (2) the fission products Tc and I for inclusion in ATW transmutation assemblies, and (3) the uranium in a form that can be disposed of as a Class C low-level waste. A baseline process and two backups are being researched to accomplish these tasks.

The baseline separations process is 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 U stream for waste, technetium and iodine streams for target fabrication, and a TRU-fission product oxide stream. The EM process would then separate the TRUs from the fission products and convert the TRUs to a metallic form suitable for fabrication of ATW fuel.

The recommended backup 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. An “all aqueous” process would be equally viable as a backup to the baseline process; the technology for this sort of system is well-advanced, and necessary developments to make it available as a deployment option are within the scope of the baseline program.

An alternative backup process consists of an initial UREX aqueous processing step, followed by an aqueous TRUEX-based step, and in turn followed by the EM process. The UREX process would produce a pure U stream for waste, technetium and iodine streams for target fabrication, and a TRU-fission product oxide stream for the TRUEX process. The TRUEX step would then further separate the TRUs from the fission products. The EM process would then convert the TRUs to a metallic form suitable for making ATW fuel. This backup option necessitates the inclusion of a modest amount of R&D to bring the already-developed TRUEX process to a level that would permit its inclusion in the field of candidates for the selection of the reference process.

The baseline LWR process includes aqueous-based processing steps for the light-water reactor spent fuel to remove the bulk materials (zircaloy cladding and uranium). This will leave only about 4% of the original cladding/fuel mass to be processed in subsequent separations systems. The baseline process also includes isolation of the fission products iodine and technetium to enable transmutation of the long-lived ^{129}I and ^{99}Tc.

ATW fuel-processing extracts the TRU elements (for recycle into fresh ATW fuel) and technetium and iodine fission products (for incorporation in ATW transmutation assemblies) from spent ATW fuel 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. Pyrometallurgical processes are being researched for the treatment of ATW fuel because of their robust and compact nature, compatibility with the desired waste forms, and cost effectiveness. In contrast to the LWR fuel processing, high material throughput is not required for the treatment of spent ATW fuel. The projected material throughput requirement is about 100-200 kg of total fuel mass per day for likely deployment scenarios. Two options are being considered for treating irradiated ATW fuel, a chloride volatility process 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 TRU’s and fission products.

The baseline pyrochemical processes for the front- and back-end treatment operations will result in two types of high-level waste 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 form materials 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. Since ATW systems will destroy TRU actinides and the most significant long-lived fission products, ATW waste forms will not contain these long-lived isotopes. The demonstrated behavior of the ceramic and metal waste forms indicates that they will be more than adequate for application in the ATW concept.

For the first three years of this research and development program, backup processing options will be considered. One of the backup LWR spent fuel processing methods contains a TRUEX step which, if incorporated, will produce aqueous raffinate solutions and other miscellaneous waste that will contain residual technetium, iodine, and other fission products. This waste stream would require a different high-level waste form, such as borosilicate glass. High level waste form materials must be selected, developed, and evaluated for the backup processing options to provide a basis for comparison to the baseline processes.

6.7.5 System Integration and Management Costs During R&D

System integration and management costs during the ATW technology research and development period will be incurred to plan and manage cross-cutting and integration activities not addressed by the major technical system activities. The key activities considered in this estimate include:

Licensing and permitting.
Safety analyses, safeguards, and security.
National Environmental Policy Act (NEPA) planning and documentation.
Project strategies and planning.
System engineering, trade studies, and baseline management.
Technology component interfaces and integration.
Management of the ATW Project office and staff.

Table 6-7. Integration R&D Cost Estimate

R&D Task	Estimated Cost ($M)
System Studies	22
R&D Coordination	52
Total Estimated R&D Cost	**74**

The sum of all costs in Figure 6-8, *Annual Systems Integration and Management Costs*, is less than ten percent of the total ATW R&D costs.

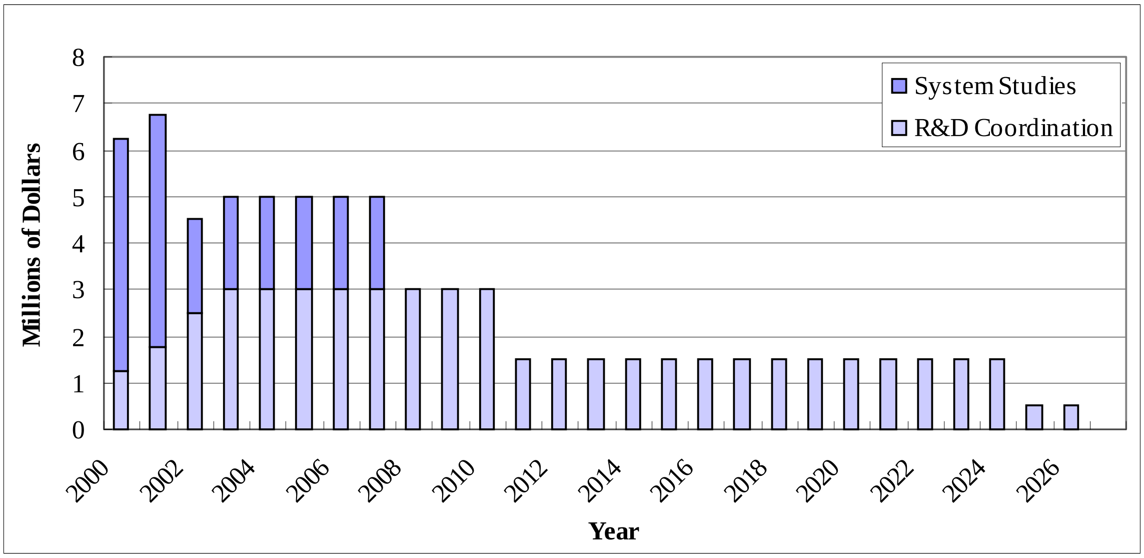


Fig. 6-8. Annual Systems Integration and Management Costs

6.8 R&D Path for Demonstration of Concept Feasibility

The R&D plans developed by the three technical working groups are highly constrained in time in order to meet an aggressive ATW deployment schedule. The major constraint on the R&D schedule is related to the startup date of the demonstration facilities in 2016, which imposes completion of the major elements of the R&D program in 2008 (accelerator R&D , coolant R&D, core design R&D, separations R&D) and in 2013 (fuels R&D).

Three conditions need to be fulfilled to meet this schedule:

- the current R&D objectives must be confirmed by the ATW trade studies. Modifications in the objectives could result in the redefinition of the R&D plans and schedules. At this point, it is quite clear that some major system parameters have not yet been well established (e.g., reliability requirements for the accelerator, fuel composition and burnup rates, separations recovery rates, operating temperatures); thus, major modifications of the R&D plans are likely.
- The R&D plans assume technical success with little scheduling contingencies for demonstrating alternate solutions.
- They also require large budgets (around $100M per year) from the start of the program.

An alternate approach would consist of relaxing the time constraint and concentrate in the first several years of the program on resolving the major technical and feasibility issues. The program would then become "science based" and instead of being schedule driven, it would prepare a solid technical basis for future deployment.

The science based approach would have several advantages:

- It would permit progress within smaller budgets
- It would postpone the deployment of expensive facilities needed for the demonstration phase
- It would enhance the probability of completing the R&D for the preferred technologies in time for deployment
- It would enhance the possibilities for international collaborations, which are generally much more attractive during the scientific phase of a project and become difficult during the demonstration phase

Finally, it can also be noted that this approach is the basis for the Japanese program which has not yet committed to a specific scenario for disposing of SNF, and seems also to be currently favored in Europe.

The Technical Working Groups have not attempted to set up such a program; rather they have concentrated on deployment driven programs. Nevertheless, discussions with the TWG chairman have provided a basis for establishing R&D priorities. The following is a brief description of the set of program elements required to demonstrate the ATW technical feasibility.

6.8.1 System Integration Task

Most trade studies described in Section 6.4 are essential to the success of a science based program. In this approach they will be used to define the objective system performance, to compare various technical concepts, choose specific technologies and define technical parameters. System sizing studies can be postponed. Due to the relaxation of time constraints, there is a great opportunity for developing these studies on an international basis and for potentially reaching an international consensus.

6.8.2 Target-Blanket Task

The feasibility of the Target-Blanket Concepts requires investigations in several areas: fuel development (Section 6.8.2.1), nuclear design and safety (Section 6.8.2.2), coolant technology (Section 6.8.2.3) and spallation target development (Section 6.8.2.4).

6.8.2.1 Fuel Development

The major scientific priorities for the fuel development program are the measurement of fuel material properties for the reference fuel form (Section 6.8.2.1.1), the fabrication studies for the reference fuel form (Section 6.8.2.1.2), irradiation studies for the reference fuel form (Section 6.8.2.1.3), and the development and demonstration of LLFP transmutation assemblies (Section 6.8.2.1.4).

6.8.2.1.1 Fuel Material Properties

The material properties of the fuel components must be either conservatively estimated or experimentally determined in order to design meaningful irradiation experiments.

A variety of metallurgical studies will be required to determine alloy solidus-liquidus temperatures, phase equilibria, and microstructural characteristics. These properties have both safety (e.g., fuel melting) and irradiation performance (e.g., symmetrical crystal structures are often best for metal alloy dimensional stability during irradiation) implications.

A variety of thermophysical properties must be estimated or measured. These include densities, thermal expansion characteristics, thermal conductivity, specific heat, etc. These properties are required to enable the design of irradiation tests such that the proper thermal and irradiation conditions are achieved in the experiments. Furthermore, the thermal properties of the fuel directly impact fuel integrity, and therefore reactor safety.

Compatibility between the fuel and stainless steel cladding must be confirmed. Of particular interest will be the class of stainless steel alloys in use by the Russians in LBE applications, and the effect of the minor actinides on compatibility. Additionally, compatibility between the fuel and the LBE must be characterized.

A number of issues related to the fuel-cladding gap must be resolved prior to fabricating the initial fuel for irradiation testing. Should an open gap and a thermal bond material be required or desired, a thermal bond material must be selected that is compatible with fuel, cladding and coolant materials.

While many material properties may be conservatively estimated for the purposes of obtaining approval for the initial irradiation experiments in test reactors, this will not be adequate to prepare a solid, technical safety case for an ATW core. The large uncertainties associated with conservative material property estimates must be reduced by a fairly comprehensive experimental program to measure the important fuel properties directly. The results of this measurement program, will encompass steady-state and off-normal irradiation conditions.

6.8.2.1.2 Fabrication Studies

It is envisioned that the metallic fuel forms proposed for the ATW can be fabricated using techniques previously employed for IFR-type fuels or currently under development for metal-matrix, reduced-enrichment fuel for research reactors. However, there is no experience with such fabrication of the fuel compositions being considered for ATW. Therefore, the suitability of the envisioned techniques must be demonstrated in laboratory experiments and appropriate fabrication parameters determined.

6.8.2.1.3 ATW Fuel Feasibility Irradiation Tests

The irradiation tests are designed to collect data relating to the feasibility of both candidate fuel forms. As currently conceived, these irradiations would likely be conducted in the Advanced Test Reactor (ATR), which is viewed as the fastest path to gain initial performance data. The first irradiation test would attempt to gain data at nominal conditions for an ATW fuel. If data from the first test appears promising, the second test would attempt to evaluate more aggressive, bounding-type irradiation conditions; otherwise the second irradiation test would be used to further explore fuel form options at nominal conditions.

6.8.2.1.4 Tc and I (LLFP) Target Development and Demonstration

A decision must be made as to the form in which Tc and I will be introduced into an ATW transmutation blanket. While it may be possible to incorporate these elements into the ATW fuel proper, there are also advantages to their irradiation and transmutation separately in target elements. Depending on the pyroprocess scheme to implemented, these fission products may emerge from the separations process as distinct streams and must be reintroduced into the fuel alloy system if desired to be integral with the fuel. If separate transmutation targets are to be used, the form of those targets must be determined. Alternatively, it is also possible that Tc fission products in recycled ATW fuel will remain with matrix Zr, to be incorporated in the fuel as a dilute alloy in the matrix Zr. It has been initially proposed that the Tc extracted from the incoming LWR fuel be irradiated as part of a noble metal alloy that should be able to perform well under irradiation to high exposure, which would be desired if a once-through deep-burn concept were pursued; otherwise, a Tc recycle concept would need to be developed. Iodine could be irradiated as a salt powder (e.g., NaI), providing for the produced Xe gas to be readily released to a pressure plenum included in the target element.

It is unlikely that the Tc and I transmutation targets will be capable of achieving final burnup by irradiation in a "once-through" cycle due to physical and/or mechanical degradation of the target element sin the case of Tc and gas production in the case of I. Thus, recycle of the long-lived fission product transmutation targets will need to be investigated. Recasting of the noble metal target and fabrication into new target hardware may be required in the case of the Tc. If the iodine is irradiated as NaI, then perhaps additional fission product iodine will need to be reacted with the free Na. These recycle processes might be fairly simple. Alternatively, a more complex separation process may be required.

Assuming the decision is made to transmute Tc and I fission products by means of special target assemblies, these target designs must be tested and demonstrated. These tests should demonstrate target neutronic (transmutation) performance as well as acceptable physical behavior; thus, they should ideally be performed in a fast reactor such as BOR-60, unless FFTF is available. The physical performance issues to be resolved/demonstrated are primarily associated with dimensional stability under irradiation of the noble metal alloy for the Tc target and accommodation of gas generation for the I target. The impact of changes in composition due to buildup of transmutation and capture products will also be assessed.

6.8.2.2 Nuclear Design and Safety

The major priorities for the nuclear design and safety program are the development of a safety basis, and the development and validation of simulation tools.

The R&D program for safety will evaluate integrated system response during operational transients and postulated accident sequences, verify safe shut-down and decay heat removal for a range of generic sequences that potentially challenge system integrity and public safety. The safety issues unique to accelerator driven systems (e.g., source transients) and to the reference fuel and coolant technology options will be emphasized and translated into design constraints.

The R&D program element concerned with the simulation tools provides for assessment, adaptation, development, and validation of the simulation capabilities (data, methods/models and computer codes) required for ATW core design, and for evaluation of core performance and system safety characteristics. These simulation tools are also required to support the development and operation of facilities needed to develop and demonstrate ATW technologies. The effort related to computer codes is maintained over the entire duration of the ATW development program.

The tasks associated with this program element are:

-- *Nuclear Data*: The goal of this task is to ensure the availability and quality of the basic nuclear data required for analysis of ATW systems. The focus initially is on assessment of priorities, including sensitivity and uncertainty analyses, and on evaluations of key data which may not have received sufficient attention in the past (e.g., cross sections for lead and bismuth). Provisions are also made for new data measurements (at existing facilities) should the need for such measurements be demonstrated in the assessment activity. Finally, the use of integral measurements from critical experiments to reduce uncertainties in predicted ATW performance parameters, through use of formal data adjustment procedures, is planned subsequent to completion of the experimental measurements program.

-- *Neutronics and fuel cycle codes:* This task addresses the adaptation, development, testing, and validation of computer codes used to analyze the neutronic behavior and the fuel cycle performance of ATW systems. Extensions to existing codes required to model accelerator driven systems and potential ATW features (e.g., moderated LLFP transmutation assemblies) will be implemented and the resulting codes will be validated for use in ATW design and safety confirmation.
-- *Core thermal-hydraulics (subchannel analysis):* This task provides for development/adaptation and testing of a code for use in thermal-hydraulic design analysis of the ATW core.
-- *Assembly Thermal-Hydraulic Tests:* This task consists of compiling and validating thermal-hydraulic data (e.g., pin-bundle heat transfer coefficient correlations for LBE) for use in core thermal-hydraulic design and analysis.
-- *Structural analysis (thermal and radiation effects):* Computing capabilities will be developed for predicting displacements and associated stresses of core components consistent with thermal profiles and irradiation history, and for estimating the thermo-structural response of the core to variations in power and flow.

6.8.2.3 <u>Coolant Technology</u>

The major scientific priorities for the LBE coolant program are the development of the coolant technology, the development of structural materials and the study and potential mitigation of the effects of spallation products.

The first major task is to develop the ability to run a LBE coolant system by applying and verifying the existing Russian LBE coolant technology. The emphasis is on adapting the application of the coolant technology to more ATW prototypical configurations and conditions. The decommissioning and decontamination of LBE coolant will be considered as well. The important tasks to be accomplished include: replicating the ability to run LBE loops under steady-state conditions, establishing an acceptable operating condition range, establishing the ability to recover from abnormal conditions, and developing an operational LBE coolant waste management system.

The second major task is to develop adequate structural materials, which are an integral part of the coolant technology. Structural materials must be found that maintain structural performance in neutron and neutron plus proton radiation fields and are corrosion resistant to LBE coolant. A choice must be made between Russian or U.S. design structural materials. Russian ferritic/martensitic steels are known to be corrosion resistant and able to maintain adequate mechanical performance in LBE cooled reactors. Russian austenitic steels are known to perform in LBE cooled reactors, but radiation damage data is limited to low dose so additional irradiation data will be required. Russian steels may provide cost and time savings, but the quality assurance (QA) efforts to validate design and performance data for Russian steels might be extensive. Additionally, production capacity for producing some Russian steels is not currently available. If the existing Russian data is not sufficient, tests may be needed to establish a database suitable for design needs. Some promising U.S. steels have extensive radiation experience but have not been proven corrosion resistant in a LBE system. If modifications are made to replicate Russian steels, substantial corrosion and radiation tests will be required. For any choice of structural materials, there is scant data on materials' properties under the combined effect of protons and spallation neutrons, so some irradiation tests, within a coolant-quality controlled environment are definitely needed. The important tasks to be accomplished include: determining the corrosion resistance of U.S. steels to choose the steels to be used, establishing adequate mechanical property and corrosion resistance data, and ensuring the steels chosen are adequate in the unique environment of proton plus spallation neutron damage.

The third major task deals with the effects of spallation products, both on the chemical effects on coolant quality and corrosion, and the effects on system safety. This aspect is new to the Russian coolant technology. However, due to the existence of a self-healing protective oxide film on the structural materials in an actively controlled coolant environment for corrosion resistance, the very dilute concentrations of spallation products likely will not alter the coolant technology significantly. . The important subtasks to be accomplished include: calculating the expected amount of spallation products, determining the expected products from interactions between the spallation products and the LBE coolant, determining the problems associated with the introduction of these spallation products by conducting surrogate materials experiments, and determining safety and cleanup needs.

6.8.2.4 <u>Target Development</u>

The major scientific priorities for the spallation target development are concentrated on selecting the window material and assessing its properties.

The process to achieve this involves:

1. establishing design data needs (material properties such as strength, ductility and fracture toughness as a function of displacement damage, in-beam and out-of-beam corrosion resistance, swelling tendencies, etc. that are required by designers),
2. providing irradiation and corrosion test programs to satisfy the design data needs,
3. conducting irradiation tests on near prototypical structures and components that were designed, fabricated and irradiated to simulate anticipated service situations,
4. post irradiation examination and analysis of test samples, structures and components, and

5. documenting the test results and related laboratory/industrial information in a Materials Handbook that provides the designers with a single source for properties.

6.8.3 SNF Treatment Process Tasks

The scientific priorities are to develop and validate flowsheet capabilities, apply them to demonstrate the decontamination of U streams, and investigate iodine recovery methods and Tc removal from cladding.

There are a number of computer models for solvent extraction calculations with uranium. The best model needs to be selected which includes neptunium and fission products or can be altered to include data. Calculations need to be made to determine the optimum number of stages in each portion of the process to obtain the desired results. Essential data which are not in the literature must be generated in laboratory studies.

Literature review and laboratory studies are needed to determine the best method for removing iodine from the offgas stream. The process for capturing iodine must allow easy conversion for target fabrication. There must be evaluation of the need for removal of other components of the offgas and the best method for disposal of those components.

Laboratory studies are needed of reductants for plutonium which do not add waste volume. The most frequently used reductant is ferrous ion, but ascorbic acid or other similar reductants are advantageous because they would not add waste volume. Studies must ensure that reduction is complete at high acid and that the reductant or its oxidation products do not interfere with the solvent extraction process such as reducing decontamination factors or causing the formation of emulsions.

Laboratory studies are needed to confirm co-extraction of technetium and neptunium along with uranium and their separation into separate streams. The studies will validate computer models, which then can be used to optimize the overall process for pilot plant design. Laboratory demonstration that uranium will meet class C criteria is mandatory. Laboratory studies are needed for the conversion of the aqueous raffinate to solid oxides. The key problem is to determine the correct conditions of temperature and airflow to minimize volatilization of fission products such as ruthenium. In addition, studies of the safety aspects of evaporation of HNO_3 solutions containing organics will be required.

Studies are needed on hull leaching to ensure removal of all the Tc and other noble metals from the hulls. Past work has shown that HNO_3-HF mixtures gave best results, but still did not remove all noble metals. It would be preferable not to use HF since that adds volume to the waste.

For the TRUEX process, laboratory-scale studies of the extraction behavior of UREX raffinate and alternative solvent extraction processes are necessary. Computer modeling must be extended to development of a flowsheet and used in determination of optimum conditions for processing. Laboratory-scale studies to improve the extraction of Tc via the TRUEX solvent and recovery of Tc in the solvent wash are recommended, as are similar studies of alternative solvent wash reagents which will minimize the amount of unwanted chemicals (e.g., Na) added to the waste streams. Also required is the development of stripping reagents which will minimize the amount of inert materials in the TRU product stream (e.g., striping with HEDPA would add phosphate).

In the case of the EM technology, this phase will focus on demonstrating that EM is capable of performing the required separations and that it can be scaled-up to the required batch size. The end of this phase will be marked by selection of one of the three options for LWR fuel-processing step. Included in the phase re the following activities: (1) verify flowsheet chemistry for all phases of process using simulated and irradiated fuel; (2) study scale-up issues regarding all aspects of EM process; (3) development of electrodes for salt-recovery step; (4) optimization of salt-recovery step cell configuration; (5) study methods to separate Tc from Zircaloy cladding; (6) study methods to prepare non-TRU uranium; (7) study concurrent and sequential operation of solid steel and liquid cadmium cathodes (all-pyro option only); (8) study means to isolate I and Tc and prepare targets; and (9) study behavior of TRU product with regard to Am.

6.8.4. <u>ATW Fuel Treatment Processes Task</u>

The general RD&D needs for the basic studies of ATW fuel processing are: (1) establish the process chemistry and separation efficiency for the species targeted by the process; (2) obtain a preliminary material balance for each process; (3) optimize process chemistry parameters utilizing both experimental and modeling tools; and (4) establish materials behavior, compatibility and estimates of material lifetime for each process system. These studies will utilize unirradiated materials but the work will include the use of TRU elements. The results of the lab-scale studies will be used to establish a preliminary engineering design and test program for the pilot-scale studies.

6.8.5. <u>Accelerator Concept Task</u>

The major scientific priorities for the development of the large linear accelerator are concentrated on understanding the factors which contribute to a loss of reliability, and on prototyping the key components of the large scale system.

The kind of reliability needed for an ATW accelerator must be addressed both through accelerator system design (redundancy, fast fault recovery, etc.) and through equipment development (ultra-reliable components). Several test stands should be build during the accelerator ED&D program for the ATW DEMO to evaluate the failure mechanisms for equipment that causes beam interrupts. Important elements include the proton injector, RF power systems and HVDC power supplies, accelerating cavities/cryomodules, focusing and transport magnets and power supplies, and control systems. Dedicated test stands should be built and operated to enable detailed understanding of the failure mechanisms, to filter real off-normal conditions from signal noise in protection circuits, and ultimately to eliminate or compensate for the equipment failures. The goal is to dramatically decrease the frequency of beam interrupts in the accelerator (from 1 per hour that is typical of present operations at many facilities, to only a few per year).

Long-term operation of LEDA and other APT-built accelerator test facilities would provide additional test-beds for reliability engineering. In the final analysis, operation and improvement of the DEMO linac for many years will provide the ultimate tool for reaching the accelerator reliability goals that are needed in the ATW plants.

There are several accelerator technologies that need development and/or prototyping prior to final design of the DEMO linac. These include:

- High-gradient (elliptical) high-beta SC cavities
- Low-beta (spoke type) SC cavities
- Short, large aperture SC quadruples
- Cryomodules for all sections of the SC linac, constructed using the above components
- SC beam splitters and septum magnets for distributing beams to separate burners
- Beam control using micropulse chopping systems, and/or funneling schemes
- A higher efficiency RF generator, the HOM IOT
- Ultra-reliable key components, including rf power systems, injectors, magnets, etc.

References

[6-1] A Roadmap for Developing ATW Technology: Separations and Waste Forms Technology, ANL-99-15.

[6-2] A Roadmap for Developing ATW Technology: Accelerator Technology, LA-UR 99-3225.

[6-3] A Roadmap for Developing ATW Technology: Target-Blanket Technology, LA-UR 99-3022.

7.0 INSTITUTIONAL CHALLENGES FOR DEVELOPING AND DEPLOYING AN ATW SYSTEM

7.1 Introduction

The task of developing and deploying an ATW system presents both technical and institutional challenges. Innovations in both areas will be required to convert ATW from a potential to a reality.

The institutional challenges 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 a period of many decades.
- Public acceptance issues arise with respect to both the overall policy commitment to implement ATW and to the siting and operation of the required facilities.
- Regulatory/NEPA issues arise with respect to the regulatory requirements for ATW activities, the regulatory requirements for a high-level waste repository (which will provide a basis for the performance requirements of the ATW system), and NEPA requirements for development and implementation of an ATW system.

The institutional challenges to developing and deploying systems for separations and transmutation of radioactive waste (including accelerator-based systems) have been addressed in previous studies by Lawrence Livermore National Laboratory [7-1] and by the Committee on Separations Technology and Transmutation Systems (STATS Committee) of the National Academy of Sciences/National Research Council [7-2]. This analysis draws heavily on those studies. For perspective, the analysis also draws upon several earlier studies that addressed the institutional aspects of implementing a high-level radioactive waste management system [7-3, 7-4,7-7]. Review of these studies makes it clear that many of the challenges facing ATW are not unique to an ATW system, but are faced by any system for long term management of high-level radioactive waste. Options that have been developed for dealing with those challenges in the context of radioactive waste management in general may be relevant to ATW in particular.

The discussion of institutional challenges deals with the two distinct phases of development and possible use of an ATW system: the research, development, and demonstration (RD&D) phase; and the full-scale implementation phase. Some of the most significant challenges identified by earlier studies relate largely to the implementation phase.

7.2 Research, Development, and Demonstration Phase

7.2.1 Program Management

The STATS report concluded that "a tightly managed development program" would be required to develop and demonstrate the technologies required for any separations and transmutation system. This is certainly true of the RD&D program for development of an ATW system described in this roadmap. Successful implementation of this program requires coordination and integration of the activities of multiple participants and multiple DOE sites over an extended period of time.

Past studies [7-3,7-4,7-7] concluded that a mission-oriented single-purpose organization would be needed to implement a radioactive waste management program extending over a period of decades. The statutory establishment of the Office of Civilian Radioactive Waste Management (OCRWM) within the Department of Energy (DOE) to direct the development and operation of a high-level waste management system represents an effort to provide such a mission focus. The complexity of the task of developing and demonstrating an ATW system for radioactive waste management suggests that a similarly mission-focused organization may be required to accomplish the job.

The OCRWM program itself is one source of experience at coordinating the efforts of a wide range of participants (national laboratories, contractors, and one independent federal agency, the U.S. Geological Survey) in a decades-long long program for development of a radioactive waste management system. The experience of this program may be particularly relevant because it has had to deal with the challenge of designing a first-of-a-kind system in the face of unclear and evolving regulatory requirements, and conducting its work under strict nuclear quality assurance requirements in anticipation of NRC licensing (discussed further below.) The DOE's Accelerator Production of Tritium (APT) Program may also provide a valuable example of management approaches that could be applicable to development of an ATW system. The APT Program included multiple sites (DOE laboratories and a DOE production site) and multiple participants (DOE, laboratory and production site management and operations contractors, a prime design and construction manager contractor, other DOE laboratories, and universities.) Facing a lack of confidence in DOE's ability to build new facilities, the APT Program initiated a series of management innovations to address the underlying causes. These steps included use of a small, dedicated federal staff providing overall direction and oversight to a contractor project director who was responsible for the whole project and who managed the contracting team. Since management measures such as those used in OCRWM and the APT Program can be implemented by the Department without need for more fundamental policy or legislative changes, they warrant careful examination and evaluation for their applicability to an ATW technology development program.

7.2.2 Funding

The research, development, and demonstration program presented in this roadmap would require appropriations totaling $10 billion over a 30 year period. Program expenditures would average around $150 million per year for the initial research and development stages, and would rise to an average of about $450 million per year during construction of a demonstration facility, with annual peaks of about $700 million. Achievement of the schedule and cost estimates presented in this roadmap depends upon provision of the required funding over the entire period. Successful international collaboration and industrial partnerships also depend upon confidence that the federal government's participation in such efforts will be sustained. Absent a credible commitment to sustain support for an ATW development program over an extended period, it might be difficult to obtain substantial commitments from international or industrial partners to participate in collaborative ventures involving significant costs and risks.

It does not appear that the Nuclear Waste Fund could be used for development of separation and transmutation technology under current provisions of law. The Nuclear Waste Policy Act (NWPA) allows use of the Nuclear Waste Fund only for "nongeneric research, development, and demonstration activities under this Act." This has been generally understood to include only research directed toward development of a geologic repository or other facilities authorized by the Act, and to exclude research on alternative disposal systems, even though the Act (and the 1987 amendments to the Act) mandated research on such systems. Amendment to the NWPA would likely be required to allow use of the Fund for RD&D activities not directly tied to development of a repository.

Public utility commission views might be a significant consideration if use of the Waste Fund for development of an ATW system were allowable under the law. The NWPA imposes the Nuclear Waste Fee on nuclear utilities; however, public utility commissions must approve the pass-through of the costs to the utilities' ratepayers. Some public utility commissions might question such a pass-through of expenditures for ATW RD&D unless it is clear that ATW is necessary to enable waste disposal to go forward. While public utility commissions might not have such a role in an environment of deregulation of electricity generation, the direct competition such deregulation would introduce could make the electricity generators themselves very sensitive to additional waste management charges that would increase the cost of nuclear-generated electricity at the margin. These same issues would arise with respect to use of the Nuclear Waste Fund during implementation of ATW as part of a waste management program.

Whatever the source of the appropriations for an ATW development program, they would be subject to the caps on discretionary spending established by deficit control laws. This might become a significant constraint on the achievable schedule and cost for construction of a demonstration facility.

7.2.3 Regulatory/NEPA Issues

Need for regulations for ATW facilities and activities. Whether construction and operation of a federal ATW demonstration facility would be subject to external regulation is unclear at this time. However, implementation of a full-scale ATW system would certainly be subject to the same types of regulatory requirements as other parts of the nuclear fuel cycle, whether conducted by the federal government directly or through a privatization approach. In order to ensure that a demonstration facility demonstrates not only the technical and financial but also the regulatory feasibility of ATW, the regulatory requirements need to be defined clearly and the facility should be designed and constructed as if it were subject to those requirements.

The STATS Committee examined the existing regulatory structure for the entire nuclear fuel cycle and concluded that "For the most part, the fundamental federal regulatory framework needed to license the facilities required to implement S&T technology exists." However, they reported that they were unable to obtain a clear answer as to whether current law would require a license for construction and operation of an accelerator to transmute waste. They concluded that the answer would depend upon whether such an accelerator would be considered a "production" or "utilization" facility, both of which require licenses under the Atomic Energy Act. The Atomic Energy Act defines a "utilization facility" broadly to include "any equipment or device, except an atomic weapon, determined by rule of the commission to be capable of making use of special nuclear material in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public…" [7-12]. However, the STATS Committee noted that current NRC regulations limit the definition of utilization facilities to nuclear reactors not designed or used primarily for the formation of plutonium or ^{233}U. This suggests that some addition or revision to current regulations concerning utilization facilities would be required to cover an accelerator-driven sub-critical transmutation device. The appropriate regulatory structure would need to be developed before a full-scale system could be designed.

The STATS Committee also observed that state and local governments are becoming increasingly involved in regulatory activities, introducing additional uncertainties into the future regulatory requirements for S&T facility deployment. The potential effect of such state involvement can be seen in the delays in state certification of the WIPP facility for receipt of transuranic wastes containing a hazardous waste component regulated under the Resources Conservation and Recovery Act. These regulatory uncertainties might not affect activities during the RD&D phase of an ATW system. However, they need to be addressed and, to the extent possible, resolved early in the development process in order to clarify the regulatory requirements that would affect the design of the full-scale facilities required for ATW implementation.

Once the appropriate regulatory requirements have been determined, documentation of compliance with those requirements should be developed for a demonstration facility even if it is not directly subject to external regulation. Useful precedents exist for NRC review of such documentation outside of the context of a formal licensing proceeding. For example, NRC reviewed a safety analysis for the Fast Flux Test Facility prior to the start of operations of that facility. More recently, the NRC reviewed and approved a Topical Safety Analysis Report submitted by OCRWM for a generic spent fuel dry storage facility. A satisfactory NRC review of safety documentation for an ATW facility would be a strong indicator of the licensability of such facilities in a deployment phase.

Nuclear Quality Assurance requirements. Because ATW implementation would likely be subject to NRC regulation, the RD&D activities expected to produce data that would be used in licensing ATW facilities and in qualifying the resulting waste forms need to be conducted under nuclear QA requirements. Experience with both the WIPP and Yucca Mountain projects shows that conducting a scientific development program under rigorous QA requirements can be a significant challenge. This experience, particularly the experience of the Yucca Mountain project in dealing with NRC QA requirements, should be examined carefully for applicability to an ATW RD&D program.

NEPA Requirements. An ATW RD&D program will require a programmatic environmental impact statement covering activities through the construction and operation of a demonstration facility. Since these activities would precede any decision to implement ATW as part of the waste management system, that decision would be addressed in subsequent environmental documentation at the appropriate time.

Need for disposal regulations to define a performance objective. In addition to regulatory requirements for its own facilities, the ATW system must have a clear performance objective as a basis for its design and operation. Near-total destruction of all of the radionuclides of concern is likely to be neither feasible nor necessary. Decisions must be made about how much reduction is required for which radionuclides. These decisions will depend to some extent on the as-yet-unavailable EPA and NRC regulations for a geologic repository at Yucca Mountain, the potential end point for the high-level waste produced by the ATW system. (Regulations for a high-level waste repository other than Yucca Mountain exist in 40 CFR Part 191 and 10 CFR part 60. However, in the absence of any site for such a repository, it is difficult to analyze what contribution ATW would make to improving performance, and how much improvement would be required or warranted.) Improvements in repository performance to levels that are far better than required by the regulations might be difficult to justify if achievement of those levels would require large expenditures and operational impacts. An acceptable balance will have to be found between improved long-term performance on the one hand and increased operational costs and impacts on the other. Determination of this balance must take into account the fact that the repository will contain large inventories of radionuclides in defense radioactive wastes that will not be subjected to transmutation. Transmutation of these same radionuclides in the commercial spent nuclear fuel to levels much below the defense waste inventories would produce only relatively small incremental improvements in overall repository performance.

The Yucca Mountain regulations are anticipated within a year or two. Analyses of the performance of a repository at Yucca Mountain are already available, and provide a basis for assessing the potential effects of ATW. An initial analysis is presented in a separate report. Furthermore, if the repository program stays on track, the regulations (as well as the site and design) will be tested in a licensing process before an ATW demonstration facility would be designed. This will provide a much clearer understanding of what levels of performance and associated uncertainty will be required of a geologic repository for high-level radioactive waste, and how an ATW system could enhance repository performance in the most cost-effective manner.

Clarification of status of beam-irradiated materials. Operation of a high-power accelerator will make some structural materials radioactive through exposure to the beam (or beam halo) itself. Amendment of the Atomic Energy Act's definition of "byproduct material" (42 U.S.C. 2014(e)(1)) would be required to ensure that these materials are covered by existing laws and regulations applicable to byproduct materials, such as the Low-Level Waste Policy Act and the Price-Anderson Act.

Export control issues. International collaboration in developing ATW technology using high-beam-power accelerators could raise issues concerning export of proliferation-sensitive technology. Nuclear weapons proliferation concerns arise when a technology is used to produce special nuclear material (i.e. plutonium). The possibility of producing special nuclear material using an accelerator was recognized several decades ago. Since this option for large-scale production was more costly than production in nuclear reactors, it was not pursued by the nuclear weapons states, and basic science research became the primary use of accelerators. However, the ATW program would bring together different pieces of accelerator technology in a way that would increase efficiency and neutron beam power well beyond the level (about 5 megawatts) [7-10] that could be used to produce special nuclear materials in quantities that could be a proliferation concern. Because the APT program raised this issue, DOE initiated a review of how it controls the export of accelerator technology. As a result of this review, DOE has proposed a revision to its regulations governing unclassified assistance to foreign atomic energy activities (10 CFR Part 810) to require specific authorization for assistance relating to accelerator-driven sub-critical assembly systems capable of continuous operation above five megawatts thermal [7-11]. It should be noted that the Nuclear Regulatory Commission and the Department of Commerce also have authority to license the export of proliferation-sensitive items (in 42 USC 2139 and 2139a). These might also come to apply to accelerator-driven systems through the same logic underlying the proposed revision to the DOE regulation.

7.3 Implementation Phase

7.3.1 Institutional Capabilities for ATW Implementation

Full implementation of an ATW system to treat the inventory of spent fuel produced by civilian reactors would require a major commitment of management resources and funding over a period of many decades [7-2] – a fundamental institutional challenge facing any radioactive waste management system [7-3,7-4,7-7]. Past studies and experience suggest that the necessary institutional capabilities need to be developed.

It is not likely that the private sector would implement any waste transmutation system on its own, since it has neither the financial incentives nor the integrated management and decision process required to carry out the job [7-1,7-2]. The STATS report noted that under circumstances existing at the time the report was written, it appeared unlikely that there would be any private investments in new nuclear facilities absent substantial federal guarantees. If there is little incentive for private investments in nuclear facilities associated with commercial electricity generation, there would be even less incentive to invest in a system optimized not for earning revenues from sale of electricity, but rather for achievement of very long term national waste management objectives. Furthermore, the development and operation of nuclear facilities in the private sector is controlled by a highly decentralized and uncoordinated decision process involving a large number of entities each with its own objectives and constraints. It is highly unlikely that such a process would result in the carefully coordinated development and operation of the many facilities needed to achieve the national objective of waste reduction [7-1].

For these reasons, both 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 [7-1,7-2]. The STATS Committee further concluded that the experience of federal involvement in nuclear facility development does not give confidence that the federal government has the needed capacity. Similarly, a 1982 Congressional Office of Technology Assessment (OTA) study concluded that questions about the institutional capacity of the federal government to carry out a long term program were an important cause of lack of confidence in the federal government's high-level radioactive waste management efforts [7-3].

The fundamental challenge is to assure that adequate and stable management and financial resources are devoted to the task over a period of many decades.

Management resources. Studies [7-3,7-4] that have examined the organizational requirements for implementing a federal commitment to a high-level waste management program have concluded that a significant change from "business-as-usual" would be needed. As discussed above, existing management models within the DOE may serve adequately for the RD&D phase of ATW. However, resolution of concerns about the institutional capacity of the federal government to carry out a long-term, technically and institutionally challenging program may require consideration of more extensive organizational changes for the long implementation phase of an ATW program. The studies of high-level waste management institutional issues [7-3,7-4,7-7] concluded that the organizational challenges went beyond the question of the appropriate management tools and mechanisms to the more fundamental problem of assuring that such tools and mechanisms are consistently applied to the task over a period of many decades. All of these studies determined that a mission-oriented organization dedicated only to implementing a radioactive waste management program would be required. The Advisory Panel on Alternative Means of Financing and Managing the radioactive waste program (the AMFM Panel), established by DOE in response to a requirement of the NWPA, recommended establishment of a single-purpose federal waste management corporation to provide the mission focus, independence, and stable funding they judged to be necessary to carry out a successful program. [7-4].

Adequate and stable funding. Implementation of the ATW system described in this report would require investment of several hundred billion dollars over decades. Previous studies have consistently concluded that one of the major institutional challenges to the implementation of a comprehensive high-level waste management program is assurance of stable funding over an extended period of time [7-3,7-4,7-7]. These studies were focused on a waste management program centered on development of one or two repositories. However, these conclusions about funding challenges are clearly applicable to an ATW program that would involve siting, licensing, construction, and coordinated operation of more nuclear facilities over a comparable period of time at a substantially higher cost.

The OTA and AMFM studies recommended that program funding have some independence from the annual pressures of the normal federal budget process. One piece of the solution was seen to be a fee on nuclear-generated electricity to produce the revenues needed to implement the waste disposal program. The other was a separate account for those fees insulated from other constraints of the federal budget. The Nuclear Waste Fee and Nuclear Waste Fund established by the NWPA were intended to provide stable funding for implementation of the waste management commitments laid out by the Act. However, the experience with actual implementation of that funding mechanism does not give confidence that stable and adequate funding can be assured over an extended period of time even with a dedicated source of revenues. The difficulties arose from the fact that the expenditures from the Nuclear Waste Fund were made subject to deficit control legislation passed subsequent to the NWPA. As a result, the independence of program funding from competing budget priorities recommended by OTA and the AMFM Panel has not been achieved. Various approaches to providing greater access to the revenues from the nuclear waste fee have been proposed in legislation considered in both houses of Congress over the past five years, but none has been enacted into law.

The construction and operation of the Waste Isolation Pilot Plant (WIPP) shows that in some cases the federal government can sustain a waste management facility development effort over a period of decades. The WIPP site was first identified in 1976, and the entire process of siting, site characterization, construction, and regulatory certification has taken 23 years. However, the WIPP is a single facility costing far less than the more extensive and complex waste management systems represented by the high-level waste management program and an ATW program. Furthermore, construction of WIPP was completed before the budget control laws of the 1990s were instituted. Whether the large and sustained expenditures required for high-level waste management facilities of any kind will be possible under the current budget process is open to question. The experience with high-level radioactive waste management program suggests that providing assurance of the high levels of stable funding over the period of decades needed to implement an ATW system will require institutional innovations beyond those represented by the Nuclear Waste Fee and Fund as currently constituted.

Two possible sources of funds for implementing an ATW system to treat commercial spent fuel might be considered: the Nuclear Waste Fee and Fund (assuming the problem of access to the Fund can be solved), and the revenues from ATW electricity sales.

Use of the Nuclear Waste Fund. Even if there were greater access to the Nuclear Waste Fund, it is not clear that the Fund could be used to implement ATW under current provisions of law. The NWPA specifically allows the Waste Fund to be used for repositories, monitored, retrievable storage facilities, and test and evaluation facilities, but does not mention any other types of facilities. However, the Act also allows the Fund to be used for costs related to "the transportation, treating, or packaging of spent nuclear fuel or high-level radioactive waste to be disposed of in a repository…." To the extent that ATW is seen as treatment process that complements geologic disposal, rather than an alternative disposal technology, the current language of the Act might allow the Fund to be used for such treatment once the technology is available. If implementation of ATW were achieved through purchase of ATW services from private providers, the question of use of the Waste Fund for construction of ATW facilities might be moot.

Use of revenues from the sale of electricity. A substantial part of the cost of implementation of an ATW system is expected to be offset by the sale of electricity produced as a byproduct of heat released in the transmutation process. This in itself does not impose an unfamiliar challenge. The DOE has experience at the sale of electricity through the Bonneville Power Administration and the Tennessee Valley Authority. However, marketing electricity produced as a byproduct of operation of an ATW system may face several issues for which there are no precedents:

- Reliability of the power produced by an ATW system. Accelerators do not now have the same operational reliability as standard nuclear or non-nuclear generating plants. The reference ATW plant would generate about 2,700 MW of electricity (net) for sale – slightly more than the capacity of two large nuclear power plants. Since this entire capacity would depend on the continued operation of the ATW plant, the reliability of that operation could impact the price received for the electricity produced or even the ability to connect the system to the electricity grid at all. Improvement in the reliability of large accelerators is an important objective of the ATW RD&D phase.

- Possible conflicts between revenue-maximization and waste-minimization objectives. The principal objective of an ATW system would be the efficient destruction of long-lived radionuclides for waste management reasons. There is no particular reason to expect that operation of the system achieve that objective would simultaneously lead to maximization of revenues from the sale of the resulting electricity. Care would be needed in establishing the institutional structure to manage the effort to ensure that near-term budgetary considerations do not create pressures to focus more on revenue production than on waste destruction.

Assuming that issues associated with the sale of the electricity produced during operation of the ATW system are resolved, the problem of assuring that the resulting revenues contribute to the stability of funding for the system must be addressed. The experience with the Nuclear Waste Fee and Fund suggest that in order for the revenues from the sale of electricity to contribute to the funding of the program, those revenues cannot be treated as general revenues of the U.S. Treasury. Special provisions may be required. For example, these revenues could be treated as direct offsets to appropriations for the program. Alternatively, they could be made available to the implementing agency just as the revenues from sale of electricity by the Tennessee Valley Authority (TVA) are available to the TVA for use in constructing and operating power plants. The issue of access to the revenues from ATW electricity generation might not arise if a privatization approach is used for procurement of ATW services. In that approach, the government would pay the private operator a fee for transmutation, and the operator would sell the electricity produced in the process.

7.3.2 Regulatory/NEPA Issues

Implementation of a full-scale ATW system would require a programmatic environmental impact statement. Since the NEPA documentation for the current high-level waste management program dates from 1980 [7-9], an update of that analysis might be the appropriate vehicle for addressing inclusion of ATW as part of the waste management system. This process might be more challenging than the development of a programmatic environmental impact statement for the RD&D phase because of the potentially controversial nature of a decision to reprocess the commercial spent fuel. On this point, the STATS Committee noted that "Creating and reviewing an environmental impact statement for an S&T system may be a more contentious undertaking than was the process for drawing up the Generic Environmental Statement on Mixed Oxides, which was discontinued in the mid-1970s]." Since this issue would only be faced decades from now, it is difficult to predict now how contentious the debate might be at that time.

7.3.3 Public Acceptance Issues

An analysis of public acceptance issues associated with partitioning and transmutation [7-1] concluded that introducing partitioning and transmutation into the nuclear fuel cycle would raise potentially controversial issues not now being faced by the high-level waste management program: long-standing policy disagreements about reprocessing, and the need to site additional nuclear facilities.

Reprocessing. Whether to reprocess spent nuclear fuel to recover and reuse plutonium has been the subject of major contention since the 1970s because of concerns about the potential impact on proliferation of nuclear weapons. Recently, DOE's decision to dispose of some surplus weapons plutonium by irradiation in mixed oxide fuel was opposed by some on the grounds that it would tend to promote reprocessing and plutonium recycle. This shows 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 civilian spent fuel might be subject to the same type of opposition because they involve processing of the spent fuel and separation of the plutonium. However, there are significant features of the reference ATW system that might mitigate this potential problem. The present ATW concept does not separate weapons-usable fissile materials at any time during the process. In addition, the reference ATW facility described in this report is designed so that all of the separations and fuel fabrication activities for a single transmutation device are contained in a single building. Spent reactor fuel would be delivered to the ATW site, and only the wastes from the transmutation process would leave. Finally, since the ATW facilities would be subject to full International Atomic Energy Agency safeguards, there will be an emphasis on transparency of the separations process with respect to the fissile materials.

Facility siting. Efforts to site both high- and low-level radioactive waste management facilities have encountered substantial, and often insurmountable, difficulties in gaining public acceptance. The high-level waste repository program has been limited to examination of one site, attempts by DOE and a Nuclear Waste Negotiator to site an interim spent fuel storage facility have failed, and attempts to site new low-level waste facilities have so far been unsuccessful. A 1992 review of public acceptance issues associated with transmutation [7-1] noted that surveys since the Three Mile Island accident show strong public resistance to siting nuclear facilities in general, and nuclear waste facilities in particular, near where they live. The ATW system described in this report would require siting eight or more transmutation facilities. Such facilities might be subject to the same siting difficulties facing other nuclear facilities.

A related issue that could complicate the siting of separations and transmutation facilities could be the concern that they might become *de facto* long-term repositories for the radioactive material that is brought there. This concern has been a continuing source of resistance to interim spent fuel storage facilities by those who fear that an interim storage facility would erode national interest in, and divert resources from, a permanent repository [7-6]. The same issues might be raised about transmutation facilities, if they are seen as an interim solution that would allow spent fuel to be removed from reactor sites. If that occurs, local acceptance might depend on assurances that spent fuel brought to the facility would be treated in a timely manner and that residual wastes would not remain at the site indefinitely. An analogy might be found in the agreement negotiated in 1995 between the State of Idaho and the DOE and the Navy that, among other things, allowed DOE to bring transuranic waste from outside the state to a treatment facility at INEEL. The agreement requires such wastes to be treated within six months of receipt and shipped out of the state within six months after treatment, and that existing transuranic waste at INEEL begin to be shipped to WIPP (or another facility designated by DOE) by April 30, 1999. That deadline was met with the opening of WIPP.

The positive benefits from hosting an ATW facility might offset such potential concerns in the eyes of some communities. Efforts to find a site for a Monitored Retrievable Storage facility for spent fuel did locate communities such as Oak Ridge, Tennessee that were willing to accept such a facility, although resistance at the state level successfully blocked those efforts. The experience in Oak Ridge suggests that even when the community concludes that such a facility could be an economic benefit, the community may insist on special measures to ensure realization of those benefits and prevent or mitigate potential adverse impacts [7-8].

7.3.4 Conditions for a Long-Term Commitment to ATW Implementation

A complex, highly integrated and coordinated technical and institutional effort sustained over a period of many decades would be required in order to implement an ATW system at the scale and for the time needed to make a substantial contribution to management of radioactive waste. The STATS Committee concluded that the circumstances that would support the major long-term national commitments required to carry out such an effort were hard to visualize in the near-term. However, they identified several possible conditions that might provide the motivation for such a commitment. These can be grouped into three broad categories:

- Institutional or technical difficulties that would make development of a repository unacceptable or infeasible and that could be resolved by implementation of a separations and transmutation system.

- Developments related to use of nuclear power that would make separations and transmutation easier and/or more desirable (e.g. greater acceptance of nuclear power).

- Results of research that would make separations and transmutation technically easier to implement than the alternatives examined by the STATS Committee.

The STATS Committee went on to observe that none of those conditions existed at the time of their report (issued in prepublication form in 1995). Since the STATS Committee formulated its conclusions, there have been relevant developments in several areas.

- The prospects for a repository appear better than might have been thought at the time of the STATS Committee's report. That report cited delays in operation of the Waste Isolation Pilot Plant (WIPP) and in the Yucca Mountain project as examples of difficulties in implementing nuclear projects. The recent certification of WIPP by the EPA and the start of waste disposal operations at that facility give some basis for optimism that a geologic repository for long-lived radioactive waste can achieve regulatory approval. Independent reviews of the 1998 *Viability Assessment of a Repository at Yucca Mountain* have not identified any reasons to disqualify the site.

- There appears to be growing interest in a maintaining a nuclear option in the face of concerns about global warming [7-5]. However, while utilities are beginning to seek extensions of the licenses for existing nuclear power plants, there are as yet no clear prospects for orders for new nuclear plants.

- Some progress has been made on transmutation since the STATS report. Developments in the proposed approach to ATW that have occurred since the STATS Committee considered the subject have addressed technical concerns that they identified. The RD&D program discussed in this report is directed at resolving remaining issues and demonstrating the feasibility of the approach.

Whether the conditions for a long-term commitment to implementation of ATW will exist when the performance and cost of an ATW system have been demonstrated several decades hence is a matter of speculation. Section 3 of this report describes several possible alternative futures for nuclear power in the U.S. that could affect decisions concerning ATW. The ATW development program described in this report is consistent with the STATS Committee's recommendation of continued research and development on separations and transmutation systems so that option could be available if the circumstances supporting deployment of such system eventually arise.

7.4 Conclusion

Development, deployment, and operation of an ATW system for treatment of the projected inventory of commercial spent fuel will face institutional challenges that are similar in kind to those facing development and operation of a high-level waste disposal system. Studies of the institutional aspects of high-level radioactive waste management concluded that the institutional challenges should be considered as important as the technical challenges [7-2,7-7]. In keeping with this conclusion, the technical development of the ATW system should be accompanied by tasks to address the institutional challenges in more depth and develop recommended approaches for dealing with them.

References

[7-1] L. D. Ramspott, et al., “Impacts of New Developments in Partitioning and Transmutation on the Disposal of High-Level Nuclear Waste in a Mined Geologic Repository,” Lawrence Livermore National Laboratory, UCRL-ID-109203, March 1992.

[7-2] National Research Council, “Nuclear Wastes: Technologies for Separations and Transmutation,” Washington, D.C. National Academy Press, 1996.

[7-3] U.S. Congress Office of Technology Assessment, “Managing Commercial High Level Radioactive Waste: Summary,” OTA-O-172, April 1982.

[7-4] The Advisory Panel on Alternative Means of Financing and Managing Radioactive Waste Facilities (AMFM Panel), “Managing Nuclear Waste: A Better Idea,” Report to the U.S. Secretary of Energy, Washington, DC, December 1984.

[7-5] “Federal Energy Research and Development for the Challenges of the Twenty-First Century,” Report of the Energy Research and Development Panel of The President’s Committee of Advisors on Science and Technology (PCAST), September 30, 1997.

[7-6] Monitored Retrievable Storage Review Commission, “Nuclear Waste: Is There A Need For Federal Interim Storage?,” Report, Washington, DC, November 1, 1989.

[7-7] National Academy of Public Administration, “Building the Institutional Capacity for Managing Commercial High-Level Radioactive Waste,” Washington, DC, May 1982.

[7-8] Clinch River MRS Task Force, “Position on the Proposed Monitored Retrievable Storage Facility,” Oak Ridge, TN, October 1985.

[7-9] U.S. Department of Energy, *Final Environmental Impact Statement, Management of Commercially Generated Radioactive Waste*, DOE/EIS-0046F (Washington, DC: October 1980).

[7-10] U.S. Department of Energy, *Draft Environmental Impact Statement for Accelerator Production of Tritium at the Savannah River Site*, DOE/EIS-0270D, December 1997.

[7-11] <u>Federal Register</u>, Volume 64, No. 127, July 2, 1999, pp. 35959-35963.

[7-12] 42 U.S.C. 2014(cc)

8.0 BENEFITS FROM ATW DEVELOPMENT AND DEPLOYMENT

Accelerator Transmutation of Waste has the potential for sweeping benefits in the management and disposal of spent nuclear fuel, and potentially other radioactive wastes. In addition, development of ATW technology has the potential for benefits beyond the direct goal of transmutation of waste. This section surveys some of these potential benefits. Potential drawbacks are also discussed.

8.1 Direct Benefits

The direct benefits from ATW come from conversion of potentially problematic waste materials into wastes that are potentially easier, safer and cheaper to deal with plus useful energy.

8.1.1 Spent Nuclear Fuel Disposal

The primary benefit from ATW, and the impetus for its development, is improved management and disposal of spent fuel from commercial nuclear power production. In the U.S. about 20% of our electricity comes from nuclear power plants. As of 1998, about 38,000 tn of spent nuclear fuel had accumulated in storage, primarily at the reactor sites. By the time the current generation of nuclear power plants have operated to the end of their current operating licenses, about 87,000 tn of spent fuel will have accumulated. The U.S. DOE has a program underway to develop a geological repository to dispose of this spent fuel as well as processed high-level radioactive waste from defense activities. The initial repository has a statutory capacity limit of 70,000 tn of which 63,000 tn is currently scheduled for spent fuel. The 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 such a repository. Based on this evolving understanding of geologic disposal the potential benefits from ATW can be assessed.

Benefits for the management of spent fuel can come in several forms, including:

- Improved isolation safety, or “repository performance”
- Improved confidence in repository performance
- Design flexibility, simplicity or optimization
- Increased capacity or reduced cost

These types of potential benefits will be considered in the context of the technical topics most affected by ATW processes.

8.1.1.1 Reduction in Radionuclide Inventory

The process of accelerator transmutation will reduce the quantity of many of the radionuclides in spent fuel, and will nearly eliminate some very important ones. In general, the actinide elements will be most severely reduced. The long half-life (thousands of years to hundreds of millions of years) and large biological effect of these nuclides makes them a significant long-term concern. These actinides are nearly eliminated by ATW. One generalized measure of potential hazard is the radio-toxicity of a waste. This is a product of the decay rate and the biological effect of the nuclide. The biological toxicity of ingested spent fuel nuclides with and without the actinides present is shown in Fig. 8-1, [8-1]. This illustrates the dominance of short lived fission products in spent fuel in the early time (few hundred years) and the dominance of long lived actinides at longer times. ATW provides the potential to eliminate most of the actinide inventory and thus greatly reduce the long time hazard. In a repository, this allows a robust engineered system to effectively isolate the waste during the first hundreds or thousands of years, and reduces the demand for isolation at very long times. This demand for high confidence in isolation for 10^4 – 10^6 years represents a technical challenge unprecedented in human experience. To the extent that ATW moderates this demand for very long-term isolation, the confidence in repository safety is improved.

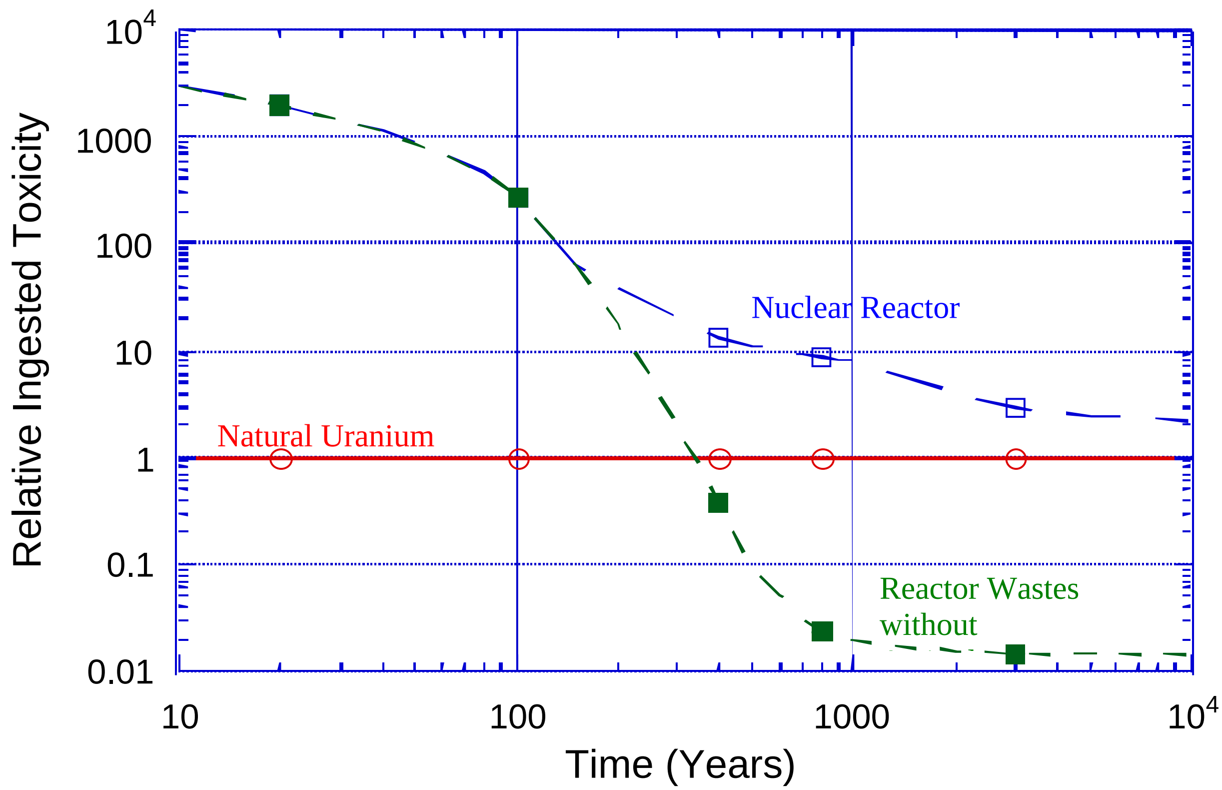


Fig. 8-1. Relative Ingestion Toxicity of Spent Fuel With and Without Removal of the Actinides

Another measure of the impact from inventory reduction can be seen from the results of Total System Performance Assessment for the "Viability Assessment of a Repository at Yucca Mountain" (U.S. DOE 1998). Through a complex synthesis of mechanistic models, probabilistic models and expert judgement, the "base case" performance of a repository is represented in a curve of "Dose Rate" to an exposed population versus time for each of the most important radionuclides. As seen in Fig. 8-2, [8-2] this dose rate (for this analysis of a Yucca Mountain repository) is dominated by ^{99}Tc out to about 50,000 years, and by ^{237}Np from that time out to 1,000,000 years, including the peak of the dose curve at around 250,000 years.

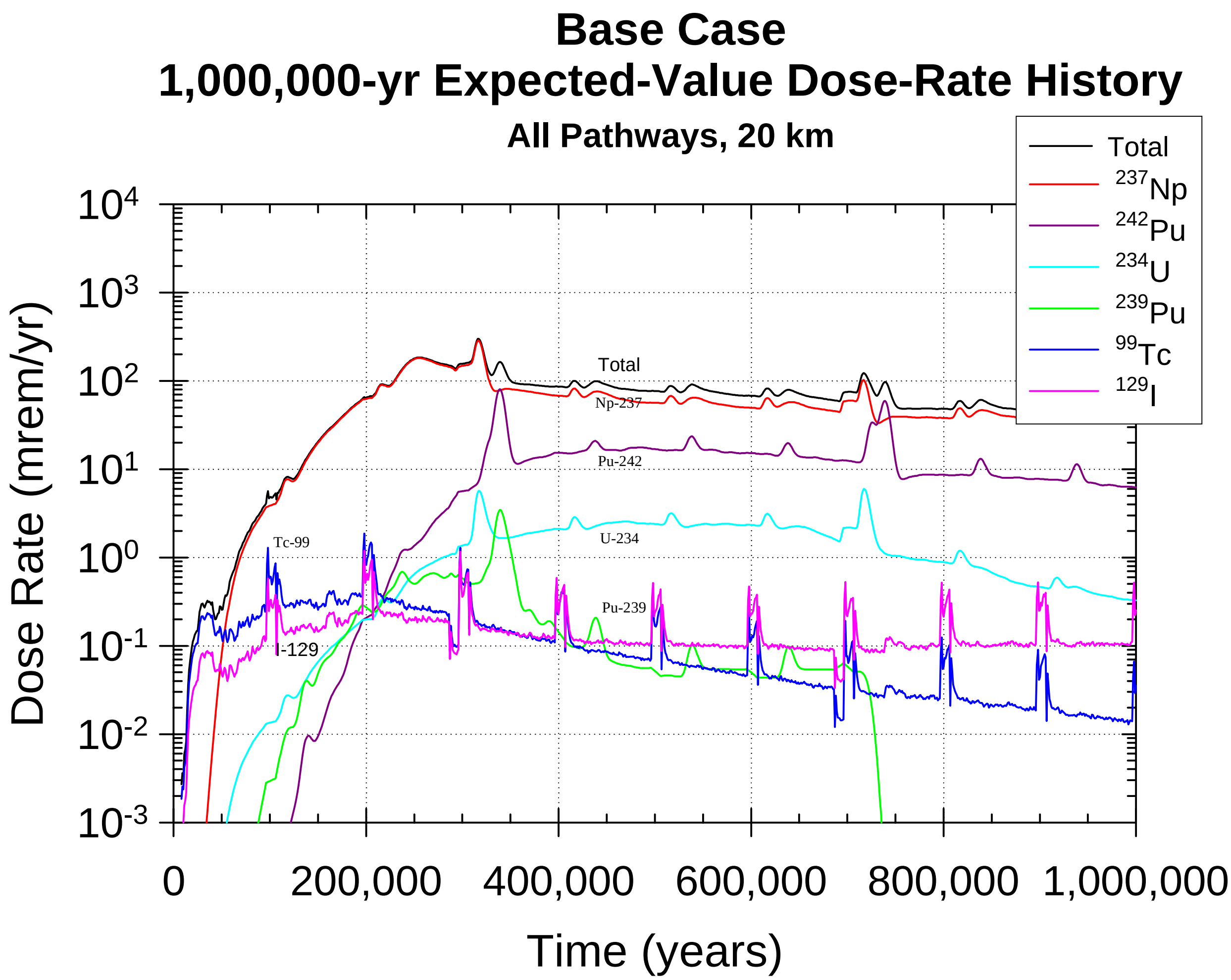


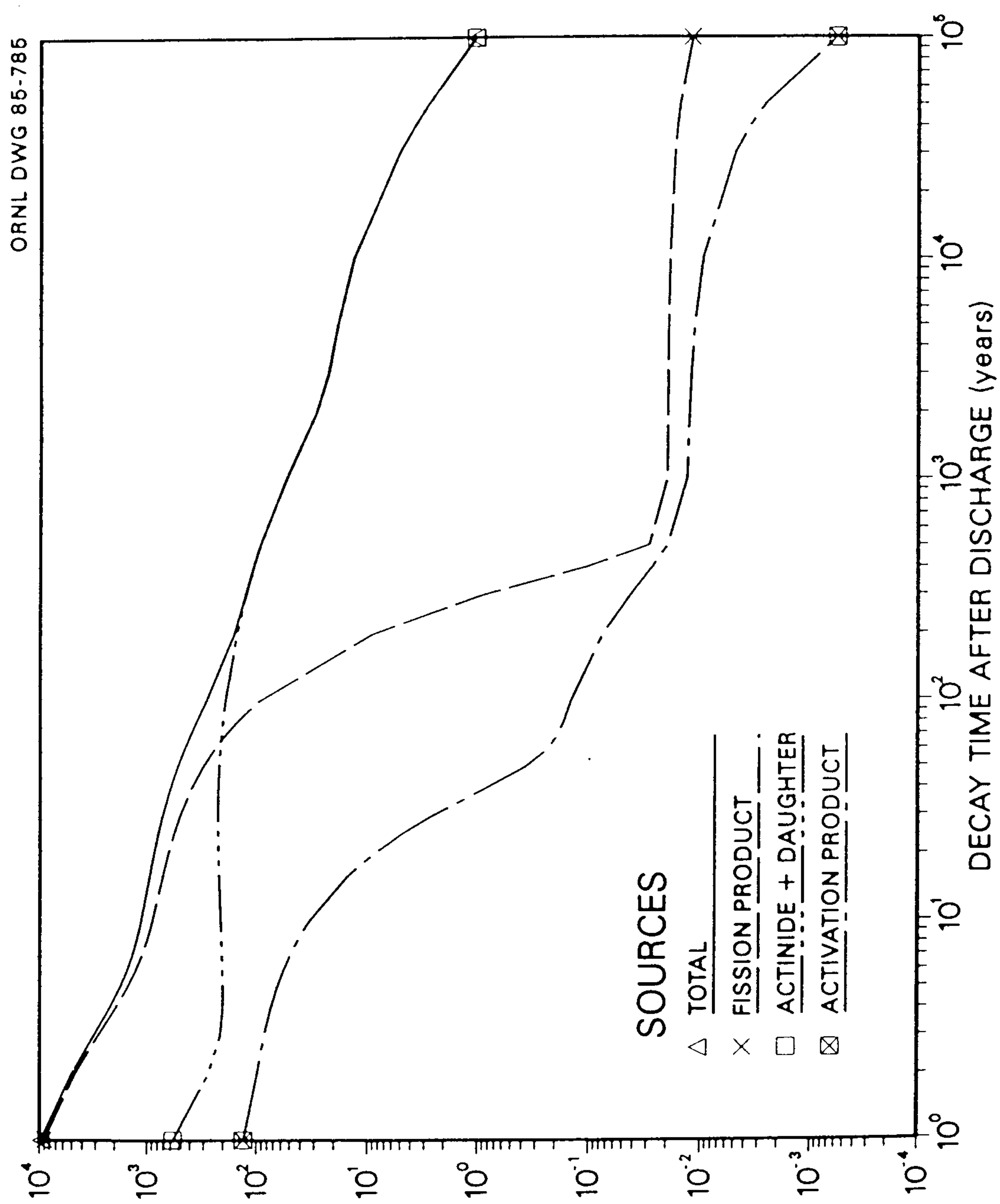
Fig. 8-2. Dose Rate Contributions from Various Radionuclides over Time

In the analysis represented here (Fig. 8-2), Tc release and mobilization is generally limited by the availability of Tc rather than its solubility, because it is highly soluble in an oxidizing environment and what little water flows through the repository is sufficient to carry away all of the available Tc. Under this circumstance, any reduction in Tc inventory will be reflected in a proportional reduction in dose rate due to ^{99}Tc. By contrast, in this analysis Np mobilization is limited by aqueous solubility limits under most conditions. That is, more Np is available for mobilization than there is water available to carry it away. Under this "solubility limited" circumstance, a moderate reduction in Np inventory does not result in a comparable reduction in dose. At later times, the decline in Np dose is due in part to complete depletion of Np from packages with higher integrated water flux. In this "inventory limited" circumstance, reduction of Np inventory due to ATW would result in some dose reduction at later times due to earlier depletion of Np inventory. However, if the Np inventory is reduced sufficiently, then Np becomes "availability limited", and any further inventory reduction is reflected in a proportional dose reduction. Under the conditions of this analysis, reduction of Np inventory by about two orders of magnitude will result in availability limited release under most conditions. An ATW system has the potential to reduce Tc inventory somewhat, and Np inventory greatly, both of which would result in lowering of the final dose rates. It should be noted that the second significant contributor to dose at early times is ^{129}I and at long times is ^{242}Pu. The Pu inventory would be greatly reduced by ATW processing, while ^{129}I could be moderately reduced. Current expectations for ATW processing result in greater than 99% removal of Pu, Am and Np, and perhaps 95% removal of Tc and I.

8.1.1.2 Reduction in Thermal Load

A feature of spent fuel (other than radioactivity) that complicates repository design, licensing, construction, operation and safety is the thermal output due to decay heat. Spent fuel can produce in excess of 1 kW/tn in the first 10-20 years after use. A repository is a closed system with slow conduction as the only heat loss mechanism. Resulting temperatures can reach several hundred C. This heat output drives many design goals and limits as well as operational issues. For example, a waste package thermal design goal for cladding (350 C) results in an upper bound on total thermal generation capacity for a single waste package of around 18kW/package. As another example, after repository closure, decay heat drives hydrothermal processes in the host rock, driving water migration far in excess of ambient percolation flow.

Fission products, primarily ^{137}Cs and ^{90}Sr, dominate the decay heat production for the first decades. Actinides dominate at long times. For typical spent fuel, the crossover point between fission product heat and actinide heat is around 60-80 years after discharge from the reactor. A representative thermal power curve for spent fuel is shown in Fig. 8-3 [8-3].



HEAT GENERATED (W)

Initial enrichment ~3.2% U-235 for PWR 33,000 MWd/MT data

Fig. 8-3. Heat Generated by 1 tn (MTIHM) of Spent Fuel: PWR; 33,000 MWd (Fig. 3.7 from J.W. Roddy, H.C. Claiborne, R.C. Ashline, P.T. Johnson, and B.T. Rhyne, *Physical and Decay Characteristics of Commercial LWR Spent Fuels*, ORNL/TM-9591/V.1, October, 1985)

ATW can have a major impact on the thermal response of a repository. In the ATW system, most of the actinides are transmuted, resulting in more fission products, but very little actinide inventory. This would skew the thermal output curve strongly to the early years. However, the fission products spend a significant residence time in the ATW system, thus allowing for more decay. If the fission product heat generation becomes a disposal issue, it would be relatively straightforward to further cool that waste long enough to allow an order of magnitude reduction in thermal output (about 100 years). With removal of the long-lived actinide heat, and viable options for short-term cooling, there is a great deal of flexibility in thermal management. This flexibility does not exist for direct disposal of spent fuel with the actinide inventory intact. This flexibility has potential benefits for repository design, waste package design, underground layout, ventilation, repository operations and long term performance.

In repository performance, there are both beneficial and detrimental aspects to heat production. Beneficial effects include driving water away from the waste packages and keeping the package and the waste from aqueous flow conditions for an extended time. Detrimental effects include faster oxidative processes on waste packages and waste forms at elevated temperatures, and faster dissolution kinetics at elevated temperatures once aqueous conditions do return. In simple terms, hot and dry can be good for waste package material performance, but warm and wet is not good.

Ultimately, at very long times, the uncertainties in predicting what thermal effects will be in the unsaturated rock-water system are significant. Thermally driven process can change rock properties, water flow paths and water chemistry. The shorter period of thermal transient resulting from ATW elimination of most of the actinides, could reduce the impact of those uncertainties on long term repository performance.

8.1.1.3 Elimination of Criticality Issue

A direct benefit to a geologic repository from removal of most of the actinides comes from elimination of any risk of criticality. Criticality control is one of the design constraints on the waste package. Neutron absorbers, flux traps, moderator exclusion, burnup credit and waste package inventory limits are all methods used to assure that spent fuel in a repository will stay sub-critical. At long times, differential leaching of neutron absorbers vs. fissile nuclides is calculated to provide assurance of criticality control. Finally, geochemical modeling is used to bound the concentration of fissile material in aqueous flow pathways and in precipitates formed far from the repository. All of these methods still only bound the potential for criticality, with significant remaining uncertainty. As long as large quantities of fissile material are involved, criticality questions and “what if” scenarios will be raised. The spent fuel inventory includes hundreds of tons of fissile materials. ATW removes nearly all of the fissile nuclides from the waste, effectively eliminating any risk of criticality at any time and from any process.

8.1.1.4 Customized Waste Forms

A significant benefit to repository performance comes automatically from the separation processing in the ATW concept. Separating spent fuel into several waste streams provides the opportunity to customize the waste forms produced for eventual geologic disposal. While commercial spent fuel is reasonably robust, it was designed primarily for several years operation in a nuclear reactor, not for millennia of radionuclide isolation in a geologic repository. Processing each waste stream from ATW into a chemical and physical form that is optimized for that waste can offer significant reduction in the release rate of radionuclides in the repository. An example of that would be putting Tc and I into dissolution resistant alloy, mineral or ceramic forms with dissolution rates lower than UO_2 or glass. This could get around the high release rate for highly soluble nuclides and result in reduced dose rates proportional to the reduction in dissolution rates.

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

The technical basis supporting documents for the Yucca Mountain Viability Assessment address key remaining uncertainties in data, models, fundamental understanding or details of implementation in performance assessment of a geologic repository. Implementation of ATW would address or change the nature of many of these remaining uncertainties. For example, in Chapter 6 of the Technical Basis Document [8-4] in the area of Waste Form, the following uncertainties were discussed as being potentially important to performance and requiring further work:

- Uncertainty in very long term cladding performance
- Uncertainty in water contact processes
- Uncertainty and wide range in radionuclide solubilities, and thus mobilization rates
- Uncertainty in secondary phase formation in UO_2 dissolution
- Uncertainty in colloid formation and transport
- Uncertainty in diffusive transport processes

The result of ATW in both inventory reduction and waste form customization would address all of these in beneficial ways. Some could be eliminated (such as cladding and UO_2 secondary phases) and others limited in performance impact (such as solubility and colloid formation).

8.1.2 <u>Material Diversion Risk Reduction</u>

A direct benefit from ATW beyond issues of geologic disposal comes in the form of reduction in risk of material diversion for weapon use. Ultimately, the most complete method of assuring that fissile material is never used for nuclear explosives is to turn it into something that is not fissile. ^{235}U and ^{239}Pu make up the bulk of fissile inventory in spent fuel and much of the proliferation concern. Some of the minor actinides however also are fissile and require safeguarding. There is an ongoing debate as to the relative attractiveness of various materials and technologies to different potential proliferants. Commercial spent fuel is one of the materials considered in this debate. In fact, one qualitative measure of comparison for proliferation resistance is the so called “spent fuel standard.” Spent fuel is considered unattractive for diversion because of the high radiation field and the combined actinide isotopics. However, spent fuel loses the intense radiation field as the fission products decay, and eventually may not meet a “spent fuel standard” itself! ATW would eliminate that concern by eliminating the fissile actinides. The present ATW concept does not separate out weapon usable fissile materials at any time during the processing.

Deployment of ATW would be a demonstration of a diversion resistant nuclear fuel cycle with enhanced energy recovery and simplified waste disposal compared to a once through cycle. This demonstration could encourage a broader acceptance of nuclear energy production, both domestically and internationally.

8.1.3 Energy Production

Another obvious benefit from an ATW system is the production of large quantities of thermal and electrical energy. One full size ATW unit as proposed in Section 4 of this report generates 2146 MW of net electric power. The 8 units in the proposed ATW campaign provide over 800,000 MW-Years of electricity during 60-100 year ATW operating period. The potential retail market value of this electricity is in the 300-500 billion $ range. This additional electricity is more than 30% of the electricity generated by the nuclear reactors that originally used the fuel. It has been suggested that such a large individual power plant 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. It uses residual energy potential in the spent fuel actinides that would have otherwise represented complications for waste disposal.

8.2 Potential Indirect Benefits

In addition to achieving the primary goals from ATW, a number of potential “spin-off” benefits could accrue from development of ATW capability.

8.2.1 Nuclear Leadership

An indirect benefit from ATW development and deployment would come in the form of advanced technology, and world leadership 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 pyro-metallurgical processing at the scale of ATW would bring this technology to the forefront, and demonstrate material diversion resistant options for nuclear fuel cycles.

Pb/Bi Technology: We would gain experience in this technology through international collaboration.

Neutron Science Research: ATW development would provide world-leading opportunities for intense neutron source research.

8.2.2 Isotope Production

ATW represents a potential source of isotopes for medical, industrial and research purposes. Insertion of targets of thorium or uranium into an ATW system would result in a small amount of fission to produce fission products. This creates one machine with the potential of producing most isotopes, with a "full" range of options for producing nuclear transformations. ATW could produce, as a byproduct, other useful isotopes via spallation and neutron capture, such as the cobalt-60 used widely for sterilization of medical instruments. Production of other isotopes is possible by adding other target materials. The medical isotope market is currently dominated by a handful of tested and approved isotopes and medical procedures. However, there are many new procedures undergoing pre-clinical studies and clinical trials, and many of these rely on the so-called "designer isotopes." Some of these will be highly successful and save many lives. The ATW capability for producing such isotopes is unprecedented, with its full range of capabilities for nuclear transformations. If needed, production of Plutonium-238 could be performed, with some impact on ATW throughput.

8.2.3 Back-up Tritium Production

Much of the core technology for ATW has been developed in studies focused on Accelerator Production of Tritium (APT). There are many similarities between APT and ATW technologies and hardware. Deployment of ATW capability could provide a source for production of tritium for the U.S. weapons program. Moderate quantities of tritium could be generated by substituting tritium breeding elements for a number of fuel elements in operating ATW systems. Replacing one or more ATW subcritical assemblies with APT assemblies and dedicating all or part of the accelerator beam to this purpose could provide larger quantities of tritium. Finally, the technology development and deployment for ATW would make dedicated APT systems readily deployable.

8.2.4 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, the accelerators have been used for delivering pulsed streams of neutrons, and reactors have been used when large quantities of neutrons are desired on a continuous basis. However, problems in building new research reactors, in addition to a spallation target's advantage of much lower heat generation per neutron, suggest that accelerators may become viable to produce a larger share of the neutrons used by researchers.

While we use ATW to transmute waste, other concurrent transformations would be taking place that might help answer some of the fundamental questions of forefront science. For example, ATW would be a source of neutrinos several hundred times more intense than any comparable source on earth. Because neutrinos interact so weakly with matter, we know very little about them, but they are one of the keys to understanding the origin and ultimately the future of the universe. The neutrinos generated by the ATW could give researchers a unique opportunity to study neutrino properties, and thus, learn much more about an important and somewhat mysterious part of our universe. On the other end of the scale, our understanding of how materials change when they are irradiated is largely determined through experience. For decades, scientists in the fusion community have wanted a source of neutrons like that found in the ATW target to simulate a fusion reactor environment.

8.2.5 International Benefits

Development and deployment of ATW would provide international benefits as well as domestic.

International Collaboration: There are many opportunities for international collaboration and participation in the ATW program. Development of the Pb/Bi technology is one immediate example. Several other nations are currently exploring ATW technology also, creating the opportunity for international programs.

Acceptability of Nuclear Energy: A nuclear fuel cycle option with less waste hazard, simplified waste disposal, greater energy supply and improved diversion resistance could result in greater world-wide acceptance of nuclear energy.

Energy Production: The energy produced from ATW, whether domestic, or with collaborating international partners, would represent a "bonus" from what would otherwise be a waste stream.

Lowered Global Pollution: With ATW, there is the potential for global improvements in radioactive waste management as well as reduced pollution from fossil fuel usage as ATW energy replaces less environmentally friendly energy sources.

Reduction in Proliferation Risk: With international development of ATW technology, diversion resistant fuel cycles may become more prevalent worldwide, thus reducing global proliferation risk.

8.2.6 Maintaining Core Competency in Nuclear Technology

The post-Cold War DOE has the mandate to maintain core competency in certain nuclear technologies of critical national security interest to the nation. The ATW program would provide an opportunity for DOE to achieve portions of this national security goal while addressing other important issues of waste management and energy supply.

References

[8-1] G. J. Van Tuyle, “Technology Benefits Resulting From Accelerator Production of Tritium,” Los Alamos National Laboratory, Los Alamos, NM. LA-UR-98-2872, 1998.

[8-2] U.S. DOE 1998. “Viability Assessment of a Repository at Yucca Mountain, Total System Performance Assessment,” U.S. Department of Energy, Office of Civilian Radioactive Waste Management. Las Vegas, NV. DOE/RW-0508, December 1998.

[8-3] R. B. Stout, and H. R. Leider, 1998. “Waste Form Characteristics Report,” Lawrence Livermore National Laboratory, Livermore, CA. UCRL-ID-132375, December 1998.

[8-4] RWMS M&O 1998. “Total System Performance Assessment – Viability Assessment (TSPA-VA) Analyses Technical Basis Document, Chapter 6, Waste Form Degradation, Radionuclide Mobilization, and Transport Through the Engineered Barrier System,” TRW Environmental Safety Systems Inc., Las Vegas, NV. B00000000-01717-4301-00006 REV 01, November, 1998.

9.0 INTERNATIONAL PROGRAMS FOR WASTE TRANSMUTATION

9.1 International Fuel Cycle Applications of ATW

This section describes the options that foreign countries are pursuing in the area of nuclear waste transmutation. The efforts of most fall in three generic areas: (1) mixed-oxide (MOX) fuels in LWR's, (2) Waste transmutation (including Pu and MA) in fast critical reactors, and (3) Waste transmutation in accelerator-driven subcritical assemblies.

The importance of understanding the differing international approaches is two-fold. First, a good understanding of the objectives of the different groups may assist in the development of the directions and objectives of the U.S. program. Second, as R&D proceeds, it will be important to collaborate with other international programs to reduce duplication of efforts and associated costs, and to maximize the benefits of research in topics of common interest.

In the U.S., ATW is usually considered in the context of the spent fuel legacy as part of a once through fuel cycle. Other nations are pursuing ATW as an integral component of different fuel management schemes. These different schemes lead to differing requirements for an accelerator-driven system in each case. The differing approaches adopted by these organizations, illustrated in Fig. 9-1, serve to demonstrate the flexibility that ATW might offer as a component of future nuclear energy scenarios. Also, because of the time required to develop ATW technology, current assumptions regarding ATW implementation in the U.S. could change significantly by the time it is ready for deployment.

Within the U.S., current policy is to not reprocess spent fuel, implying that plutonium is waste and is to be discarded. In contrast, 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 uranium recycle, to minimize, and eventually almost eliminate, radioactive waste. ATW is used alongside 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. The European group at CERN advocates 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 cycle that may have non-proliferation and waste disposal advantages.

In all cases, the use envisaged for ATW is to destroy the minor actinides which build up in the fuel cycle and hamper efforts to demonstrate acceptability of geologic repositories.

ATW technologies are similar for the various applications represented in Fig. 9.1, the fuel form/composition will differ from application to application, which will impact separations and fuel fabrication schemes but in all cases fast spectrum liquid metal cooled systems are the current reference.

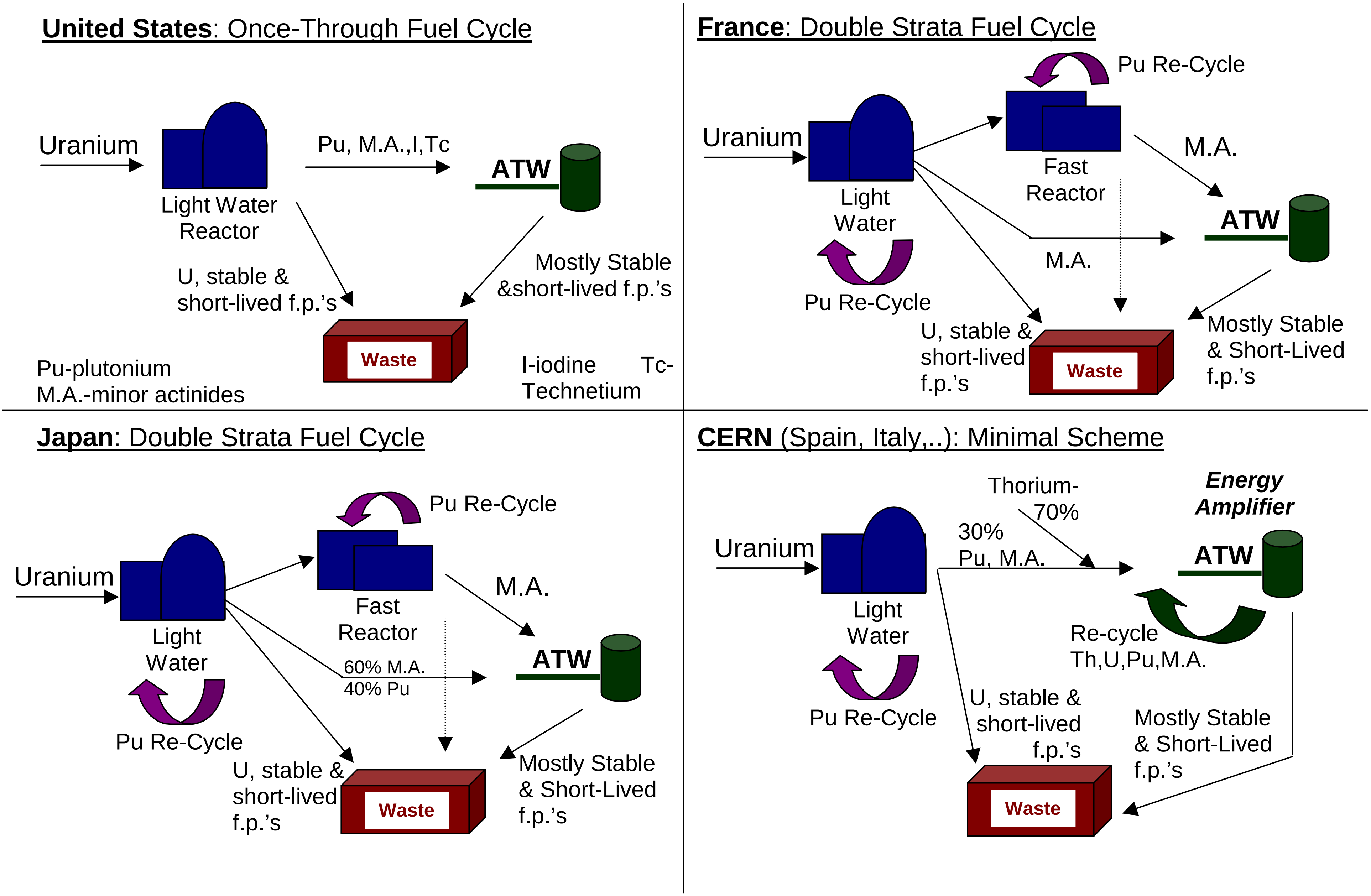


Fig. 9-1. International Fuel Cycle Applications of ATW Concepts

9.2 International Waste Transmutation Programs

9.2.1 France

The primary French objective is to develop specific technologies as an element of a national waste management strategy. The goal is to keep options open, and be able to reach a waste management decision in the future based on firm technical grounds. This is described as a science-based approach. To this end, France is following a national program to establish feasibility of a large spectrum of partition and transmutation (P&T) 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 effort is of the order of ~80 man-year/year for the current R&D stage, which includes a large-scale international collaboration (see below).

Fuel reprocessing is based on "wet" technologies, but pyrometallurgical technologies are being considered. Sodium, LBE and gas are being pursued as coolant options.

9.2.2 European "Energy Amplifier" (CERN, Italy, Spain and France)

The European "Energy Amplifier" is a concept that originated in CERN, and it involves a cooperation between Italy, Spain, and France. The objective of the Energy Amplifier concept is dual: (1) burn actinides, and (2) power production through a Thorium cycle. R&D resources are pooled between the different countries to reduce overall R&D cost. The Energy Amplifier concept has received strong support from the European Union, with the goal of helping members solve their various nuclear waste problems. The size of the present effort is hard to quantify, but it is expected to be larger than 100 man-year/year in the near future.

The Energy Amplifier concept is an accelerator-driven subcritical pile using Thorium + Minor Actinides fuel. The primary target and coolant option is molten Pb-Bi, but other options such as Pb, Na, or gas-cooling are being considered.

Current demo plans include a small-scale fissile target in CERN by 2003. LAESA (Spain) is also proposing to build an Energy Amplifier demo facility using a 380 MeV 5 mA cyclotron with a molten Pb-Bi target and a 10 MW sub-critical pile (k_{eff}=0.9).

9.2.3 Japan

Japan has active R&D efforts in the areas of fast LMRs and fast-reactor actinide burners. Even though a long-term HLW strategy has not yet been fully defined, Japan is pursuing a combination of LWR, LWR-MOX, LMR, Actinide Burner, and ATW. They have active R&D projects to examine a long term P&T strategy for long term HLW disposal.

Present plans include a Test facility in ~2009. The decision point for implementing a P&T strategy is ~2030.

Japan is pursuing nitride fuels composed mostly of minor actinides. Coolants considered are LBE, Na, He, and Pb. Their processing technology is aqueous based, but significant research into pyrometallurgical processes is being conducted.

9.2.4 Russia

Russia has significant projects in the area of waste transmutation, but they mainly concentrate on Pu disposition. To this end Russia is pursuing a combination of LWR, LWR-MOX, and fast reactors (LMR and gas cooled). MINATOM has recently begun a program to investigate ATW technology.

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

9.2.5 International Science and Technology Center (ISTC) Programs

The ISTC has funded a number of projects over the past several years in various technology areas (e.g., nuclear data, molten salt, Pb-Bi) related to ATW. Currently, a number of ATW-related projects are being supported. The Institute of Physics and Power Engineering (IPPE) is building a prototype Pb-Bi target which will be brought to LANL and irradiated in the proton beam at the LANSCE accelerator. This project is a joint effort between LANL, France, and Sweden. ISTC is also funding a project on molten salt technology which is of interest to several of the parties. The ISTC projects in Accelerator-Driven Transmutation Technologies (ADTT) are reviewed by a Contact Expert Group (CEG) which provides recommendations on which projects to fund, and advises on work scope/direction. The CEG includes members from the U.S., France, Italy, Germany, Japan, Sweden, Norway, and the European Union.

9.2.6 Other Programs

Many other countries are active in pursuing research into Accelerator-driven systems. Germany has recently received funding from the government to pursue research in this area and has built large-scale Lead Bismuth facilities at FZK 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. These concepts and others were discussed at the recent Accelerator-Driven Transmutation Technologies Conference in Prague, June 1999.

It is especially worth noting that the European Union is planning a new program, the 5th framework program, which will start shortly. Funding levels are expected to be in excess of $15M per year and will be highly leveraged by national programs. Furthermore, both the IAEA and NEA have sponsored and continue to sponsor international studies to compare the various features of ADS.

9.3 Proposals for International Collaboration

It is useful at this point to remember that the technical reference selected for this study is not the product of a systematic design optimization. Therefore, proposals for international collaboration are limited to general areas rather than specific technologies. There is one exception to this caution, that of Lead-Bismuth eutectic, where by far the predominant experience lies in one country, Russia.

The first year of the proposed R&D emphasizes a number of trade studies intended to confirm the technology choices, achieve a preliminary optimization and establish an independent basis for the U.S. program. However, the USA is several years behind the other international groupings who are pursuing versions of this technology. The most effective means of establishing a presence would be to participate in internationally organized studies and to begin formal contacts with groups undertaking or funding research (such as the EU).

<u>Proposal 1:</u> To assist in the trade studies the USA should initiate and actively participate in internationally organized studies of the technology, the benefits and the limitations of Accelerator Driven Transmutation Technologies. Such studies are already underway under the auspices of the OECD/NEA and other groupings.

As the U.S. technology choices become clear two new opportunities present themselves. First some choices will be similar to technologies chosen in other national programs. In these cases true research collaboration should be sought in order to share cost and risk. This might take the form of shared sponsorship of facilities and experimental programs or comparative studies. It is important that collaboration begin as soon as possible. The level of investment worldwide is increasing dramatically and if there is excessive delay on the part of the U.S. it will be in a weakened position to participate as an equal partner.

For national programs that are following different technical paths, exchanges of information on an annual basis should be sought.

<u>Proposal 2:</u> The USA should seek active collaboration with other countries pursuing similar technical options up to and including international demonstrations. These collaborations should initially take a science-based approach and include work on LBE (see below), nuclear data, thermal hydraulic data, material properties and simulation codes. The USA should organize systematic exchanges of information with those countries on different technical paths.

Lead-Bismuth Eutectic (PBE) technology is currently based in one country, Russia. In order to determine whether PBE can fulfill its promise as a technology for ATW application collaboration with Russia on this subject is essential. Given current economic conditions in Russia, this collaboration will require significant investment by the U.S. However other countries such as Germany and France are investing in PBE technology.

<u>Proposal 3</u>: The USA should pursue collaboration with Russia and other countries on Lead-Bismuth Eutectic Technology.

10.0 SUMMARY AND CONCLUSIONS

This report is the product of the Systems Scenarios and Integration Working Group of the ATW Technology Roadmap project. The working group met three times, March 15-18, 1999 in LANL to be introduced to ATW technology, May 6-7, 1999 at ANL to discuss progress on the report and finally May 25-26, 1999 at ANL to resolve outstanding issues and finalize the report contents. The working group included representatives from ANL, BNL, ORNL, INEEL, LANL, LLNL, SNL, WSRC, various offices of DOE, and TRW the M&O contractor to DOE/RW. Important support was provided by PNNL, the main contractor to DOE/RW for the roadmap.

The main results of this report are a detailed plan for the R&D phase, a roadmap, and discussions of the potential for international collaboration, the institutional issues which face any attempt to pursue ATW R&D and deployment and the benefits which might accrue if the project is successful.

Three other technical working groups are providing detailed plans for technology development in the areas of accelerators, target/blanket and separations [10-1,10-2,10-3]. The reader is referred to the reports of these working groups for more technical detail. Similarly two other studies were commissioned as part of the ATW Technology Roadmap; one addresses the potential impact on the existing repository program while the other addresses life cycle costs. Both of these studies address specific questions in the congressional mandate.

This report uses as its reference a fast spectrum liquid metal cooled system. Sodium coolant is chosen simply because it represents the lowest technical risk and an excellent basis for estimating the life cycle cost of the systems exists in the work carried out under DOE's ALMR (PRISM) program. For ease of technology transfer from the IFR program metal fuel and associated pyrochemical treatment is assumed. Similarly a linear accelerator has been adopted as the baseline.

It is important to recognize that no attempt has been made to compare and contrast accelerator-based systems with reactors. Neither has any attempt been made to optimize the design within the chosen technologies. In fact, trade studies intended to lead to design optimization are a key recommendation for the first year of any serious R&D program.

The main technical issues in the ATW system turns on the need to dispose of the energy created in the transmutation process. The amount of energy is too large and potentially valuable to be simply discarded. As a result each ATW system becomes a large energy park with a net output of 2100Mwe, comparable with nuclear sites such as PaloVerde, together with associated fuel treatment facilities and accelerators.

In the R&D roadmap, Fig. 10-1, key technical issues are identified and timescales proposed for the resolution of these issues. For the accelerator the main issue is the achievement of the necessary reliability in operation. To avoid frequent thermal transients and maintain grid stability the accelerator must reach levels of performance never previously required. For the target material the main technical choice is between solid or liquid targets. This issue is interlocked with the choice of coolant. Lead-Bismuth eutectic is potentially a superior choice for both these missions but represents a path with greater technical risk. In the case of the blanket and sodium coolant metal fuel has been selected. Metal fuel is the obvious choice due to the positive experience gained in the U.S., and also due to the possibility of associating it with a set of proliferation resistant partitioning techniques. Other technical options exist, such as the nitride option being pursued in Japan; the choice of a different fuel type might also require the development of new separation techniques.

The reference method of processing of spent fuel from LWRs to provide the input material for ATW is chosen to be aqueous because of the large quantity of Uranium that needs to be brought to a state that it can be treated as less than Class C waste. Again this is the path of least technical risk although the pyrometallurgical option will be pursued as an alternative. Processing of the TW fuel after irradiation in ATW will be undertaken using pyrometallurgical methods. The transmutation of Tc and I represent special issues and various options will be pursued to achieve these goals.

Finally the system as a whole will need optimization from a reactivity and power control perspective. Varying accelerator power is feasible but can lead to overdesign of the accelerator; other options are movable control rods, burnable poison rods, and adaptations of the fuel management strategy.

Other countries and international groups are pursuing Accelerator-Driven Transmutation Technologies. There are clear synergies between any program in the U.S. and the programs in France and Japan and many opportunities for technology partnerships. More intriguing is the CERN grouping led by Prof. Rubbia, who are pursuing the Uranium/Thorium cycle. This cycle is not a subject of U.S. interest today but one that bears promise. It should be noted that collaboration on the subject of separation technology is likely to be difficult because of U.S. policy restrictions related to Special Nuclear Technology (SNT).

The ATW technology roadmap developed here is success driven and therefore describes an aggressive path to implementation of ATW in the USA. There are; however, three technical issues that need to be addressed before the USA should commit itself to such a path; one is the technical risk that the repository performance may not be significantly improved, the second is that the overall cost is simply too large for the expected benefit and the third is the proliferation potential of ATW-like systems. The first two of these issues are subjects of separate studies within the ATW Roadmap project.

Similarly there are institutional issues which might provide barriers to development and implementation of ATW. These issues are the ability of the federal government to provide the necessary resources to carry out an ATW program, public acceptance of both policy and siting of facilities and the regulatory requirements for ATW. These challenges are likely to be less demanding during research and development phase of any ATW project.

Three specific proposals for the form the collaboration might take have been given earlier. They are:

<u>Proposal 1:</u> To assist in the trade studies the USA should initiate and actively participate in internationally organized studies of the technology, the benefits and the limitations of

Accelerator Driven Transmutation Technologies. Such studies are already underway under the auspices of the OECD/NEA and other groupings.

Proposal 2: The USA should seek active collaboration with other countries pursuing similar technical options up to and including international demonstrations. These collaborations should initially take a science-based approach and include work on LBE (see below), nuclear data, thermal hydraulic data, material properties and simulation codes. The USA should organize systematic exchanges of information with those countries on different technical paths.

Proposal 3: The USA should pursue collaboration with Russia and other countries on Lead-Bismuth Eutectic Technology.

Such a program will keep the U.S. in contact with developments in nuclear technology world-wide and help to preserve U.S. leadership in nuclear issues. The direct benefits could include improved repository performance (reduction in radionuclide inventory, elimination of criticality concerns and customized waste forms) and the energy production from spent fuel.

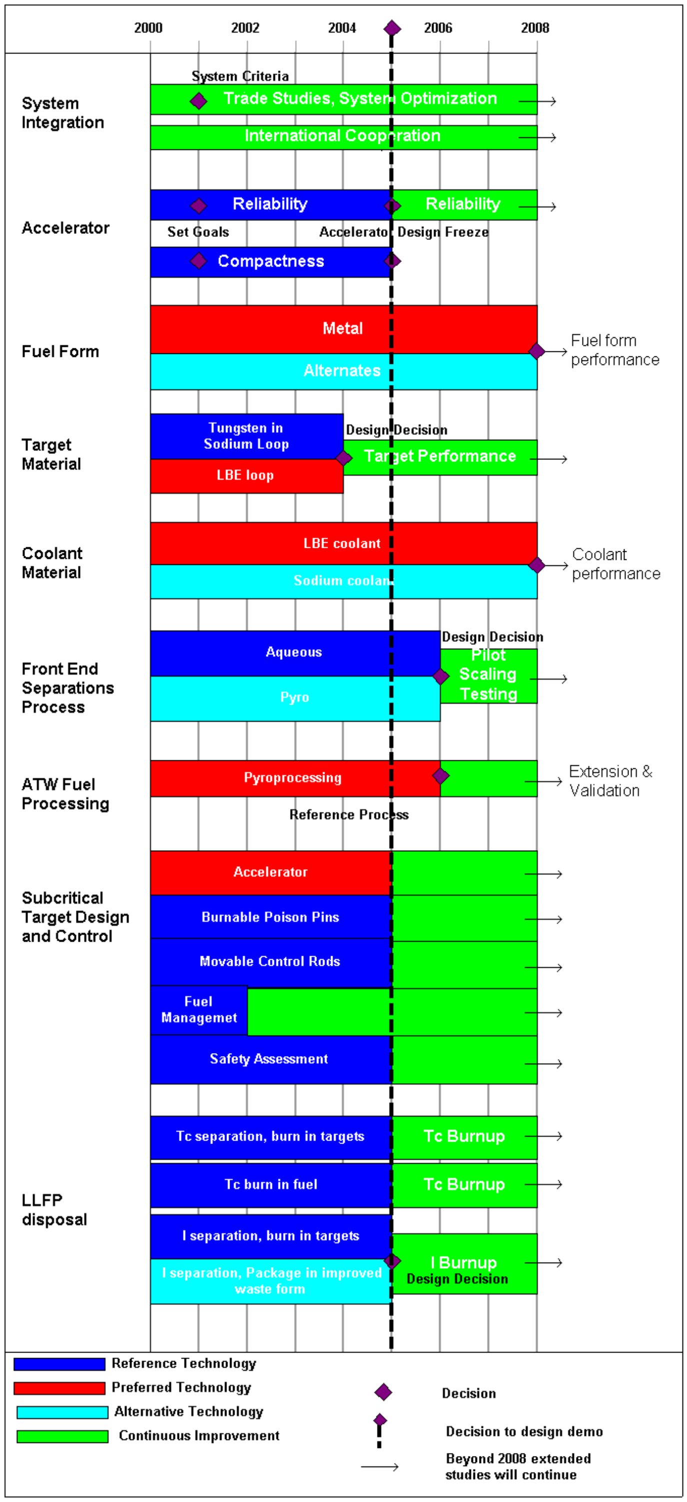


Fig. 10-1. R&D Roadmap

References

[10-1] A Roadmap for Developing ATW Technology: Separations and Waste Forms Technology, ANL 99-15.

[10-2] A Roadmap for Developing ATW Technology: Accelerator Technology, LA-UR 99-3225.

[10-3] A Roadmap for Developing ATW Technology: Target-Blanket Technology, LA-UR 99-3022.

APPENDIX A. HISTORICAL AND PROJECTED PRODUCTION OF SPENT FUEL, TRU, AND FISSION PRODUCTS FOR THE REFERENCE U.S. SCENARIO

The production of spent fuel and the contents of that spent fuel (transmuted light elements, fission products, uranium, and TRU) depend on burnup history of the spent fuel. Parameters that characterize burnup include variations in the power level (neutron flux and fission rate) of the fuel during irradiation, the concentrations of uranium isotopes in the feed fuel, and interim down times during irradiation. Down times are important because they allow radioisotopes to decay before they are exposed to neutrons which may transmute them or induce fission. This appendix includes a description of the methods and historical data that were used to calculate quantities of spent fuel, TRU, and fission products produced (discharged) for the scenarios presented in sections 4 and 5. It also includes a table of historical data and projections of reactor capacity and performance, of spent fuel discharges, and of annual and cumulative TRU production from 1990 to 2036.

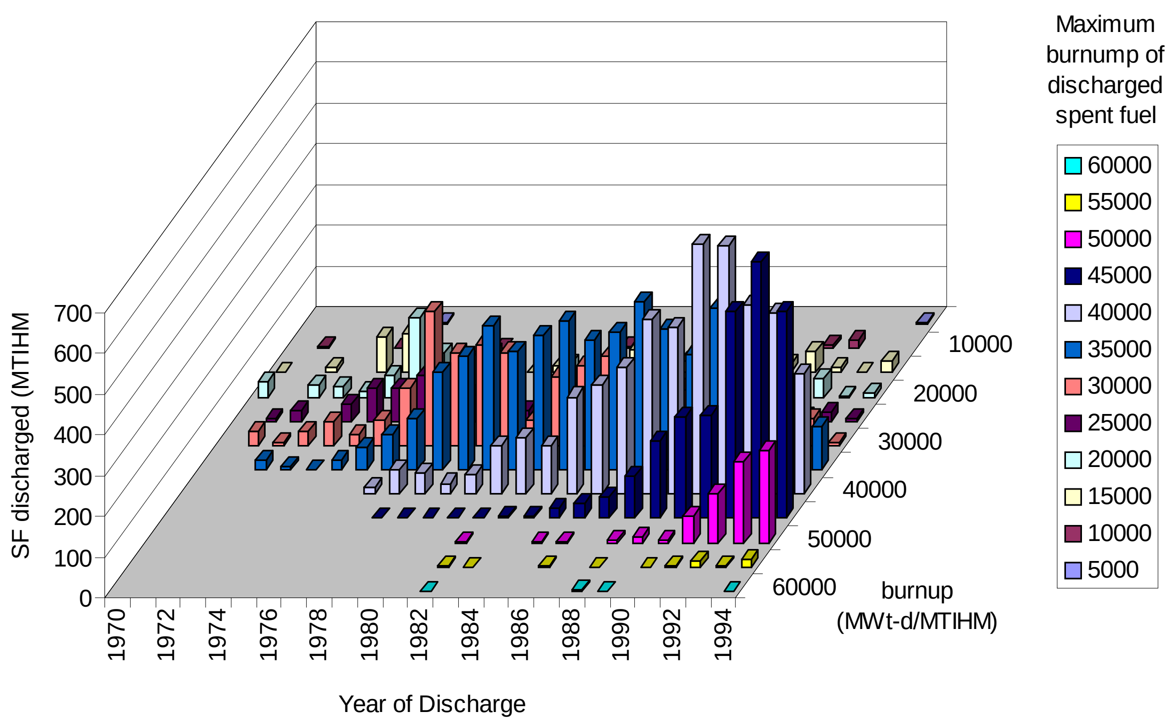


Fig. A-1. Burnup distribution of spent fuel discharged from U.S. BWRs, 1970 to 1994

The spent fuel production is based on several Integrated Data Base reports issued by the U.S. Department of Energy. Historical data on spent fuel quantities discharged through 1994, with distributions by year, reactor type (BWR or PWR), and burnup (by 5,000 GWth-d/MTIHM burnup bins) is contained Revision 12 of the Integrated Data Base.[A-1] This data is illustrated in Fig. A-1 for U.S. BWRs. To extend this data base for use in the civilian radioactive management waste program,[A-2] TRW projected similar data out to 2036 for existing U.S. power plants.

The distribution in burnup and age is important to our analyses because TRU, Tc, and I content (including isotopic concentration) depends upon burnup and decay time before separations for ATW use, which could occur between 40 and 100 years after discharge. For other than the Reference Scenario, projections of burnup beyond 1994 are based on an historical capacity through 1998, then DOE's projected capacity,[A-3] historical or average capacity factors (varies from 78.6% in 1998 to 85% in 2015, constant thereafter), and average thermal-to-electric conversion efficiency (33%). With the historical or projected spent fuel production and burnup distribution, a projection of TRU and Tc and I production is made.

TRU production depends on burnup and decay time, and for purposes of estimation, lower burnups can be assumed to have longer decay times and higher burnups shorter decay times. A suite of fuel burnup/depletion codes and cross sections was used to develop a relationship between TRU production and burnup. The SAS2H[A-4] depletion analysis driver from SCALE 4.4[A-5] was used for this analysis along with a 44-group ENDF-B/V[A-5] cross section library. The results of these analyses are presented in Fig. A-2. The figure includes results of SAS2H calculations with generic BWR (8x8 assembly) and PWR (17x17 assembly) fuels and an exponential fit to both sets of data with the following equation (units of burnup are GWth-d/MTIHM, units of TRU production are the same as the coefficient, tn TRU/MTIHM):

$$\text{TRU production} = (0.00125 \text{ tn TRU/MTIHM}) \times \text{burnup}^{0.591}$$

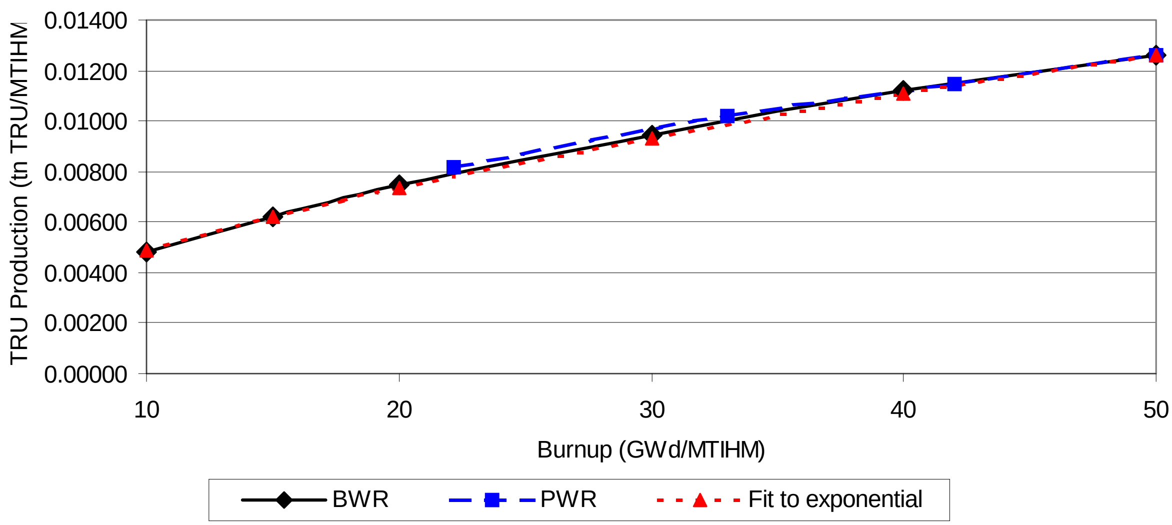


Fig. A-2. TRU Production Versus Burnup of Spent Fuel Discharged from U.S. LWRs

The fit to the data was weighted to produce a better correlation at higher burnup, where most of the spent fuel is discharged and most of the TRU will have been produced by 2030. This equation was then used to calculate the production of transuranic elements from the existing and projected spent fuel data. In addition, a cumulative accounting of average burnup and average TRU discharge was used to produce an average conversion of 0.0104 tn TRU/MTIHM, or 900 tn TRU in 86,317 tn of spent fuel.[1] This average was used in the scenario analyses to calculate the annual processing quantities of spent fuel to supply given TRU feeds to ATWs. In addition to calculating TRU production versus burnup, fission product production and isotopic production of technetium and iodine was calculated. The average production for the same integral average burnup is 42.4 kg fission products/MTIHM, 0.84 kg technetium/MTIHM, and 0.24 kg iodine/MTIHM.

The above parameters and the historical and projected capacities, capacity factors, and burnups at discharge were then used to calculate quantities of spent fuel discharged, TRU content in that spent fuel, and the Tc and I associated with that TRU. The result of the calculations is summarized in Table A-1. The cumulative discharged spent fuel is 86,317 tn in 2031, and this fuel contains about 900 tn of TRU, 73 tn of technetium (^{99}Tc), and 20 tn of iodine (^{127}I and ^{129}I).

[1] Note that this TRU production does not correspond to the value obtained if the integral average burnup, 37.2 GWth-d/MTIHM, is used with the equation on the previous page. This is the average of the TRU production from a distribution of spent fuel burnup.

Table A-1. Nuclear Power Generation and Spent Fuel and Transuranics Production for the Reference Scenario. Italicized entries are historical data or were calculated from historical data. Other data are projections or estimates; generation capacity (second column) is projected by the U.S. DOE, other projections are explained in the previous text.

YEAR	LWR Generation capacity (GWe)	LWR production (GWe-yr per year)	Average capacity factor (percent)	Total Nuclear Energy (GWe-yr)	Average LWR burnup (GWth-d /MTIHM)	Annual LWR spent fuel discharged (MTIHM per year)	Cumulative LWR spent fuel discharged (MTIHM)	Annual TRU production (tn/yr)	Cumulative TRU discharged (tn)
1990	*99.6*	*65.9*	*66.1%*	*425*	*31.9*	*2,124*	*21,496*	20.4	185
1991	*99.6*	*69.9*	*70.2%*	*495*	*33.4*	*1,841*	*23,337*	18.1	203
1992	*98.9*	*70.4*	*71.2%*	*565*	*34.9*	*2,272*	*25,609*	23.0	226
1993	*99.0*	*69.7*	*70.4%*	*635*	*36.8*	*2,204*	*27,812*	23.1	249
1994	*99.1*	*73.1*	*73.8%*	*708*	*37.6*	*1,885*	*29,697*	20.0	269
1995	*99.4*	*76.9*	*77.3%*	*785*	38.8	2,399	32,096	26.0	295
1996	*100.7*	*76.8*	*76.3%*	*862*	40.0	2,258	34,354	24.9	320
1997	*100.0*	*71.8*	*71.8%*	*934*	40.4	2,364	36,718	26.2	346
1998	*97.8*	*76.9*	*78.6%*	*1,011*	41.2	1,859	38,577	20.8	367
1999	99.4	78.8	79.2%	1,089	42.6	2,278	40,855	26.1	393
2000	99.4	79.4	79.9%	1,169	42.7	1,963	42,818	22.5	416
2001	99.4	80.0	80.5%	1,249	43.7	2,063	44,880	24.0	439
2002	98.0	79.5	81.2%	1,328	43.5	2,016	46,896	23.4	463
2003	98.0	80.2	81.8%	1,408	44.5	1,854	48,750	21.8	485
2004	95.8	79.0	82.4%	1,487	43.2	1,959	50,709	22.6	507
2005	95.0	78.9	83.1%	1,566	42.3	2,019	52,729	22.9	530
2006	93.4	78.2	83.7%	1,645	42.7	1,943	54,672	22.2	552
2007	92.8	78.3	84.4%	1,723	43.3	1,784	56,456	20.6	573
2008	92.0	78.2	85.0%	1,801	44.1	1,871	58,327	21.9	595
2009	91.5	77.8	85.0%	1,879	42.7	1,925	60,252	21.9	617
2010	89.1	75.7	85.0%	1,955	42.3	1,977	62,229	22.4	639
2011	88.3	75.1	85.0%	2,030	43.9	1,796	64,025	20.8	660
2012	84.8	72.1	85.0%	2,102	39.9	2,167	66,192	23.6	683
2013	73.5	62.5	85.0%	2,164	39.6	2,252	68,444	24.3	708
2014	64.8	55.1	85.0%	2,219	37.8	2,416	70,860	25.4	733
2015	63.0	53.6	85.0%	2,273	44.7	1,305	72,166	15.3	749
2016	57.5	48.9	85.0%	2,322	40.4	1,656	73,821	18.2	767
2017	54.8	46.6	85.0%	2,368	45.2	1,238	75,059	14.6	781
2018	52.2	44.4	85.0%	2,413	42.5	1,160	76,219	13.1	794
2019	52.2	44.4	85.0%	2,457	45.0	888	77,107	10.4	805
2020	49.1	41.7	85.0%	2,499	41.7	1,220	78,327	13.6	818
2021	45.0	38.3	85.0%	2,537	40.6	1,034	79,361	11.2	830
2022	40.8	34.7	85.0%	2,572	36.0	1,177	80,538	11.8	841
2023	36.7	31.2	85.0%	2,603	38.1	1,120	81,658	11.7	853
2024	28.8	24.5	85.0%	2,627	39.2	1,243	82,901	13.1	866
2025	22.1	18.8	85.0%	2,646	37.8	919	83,819	9.6	876
2026	12.6	10.7	85.0%	2,657	31.0	1,100	84,919	9.8	886
2027	7.0	6.0	85.0%	2,663	38.7	600	85,520	6.3	892
2028	5.7	4.8	85.0%	2,668	37.6	138	85,658	1.5	893
2029	3.5	3.0	85.0%	2,671	42.1	270	85,929	3.0	896
2030	2.3	2.0	85.0%	2,673	39.4	138	86,067	1.5	898
2031	0.0	0.0	85.0%	2,673	39.4	-	86,067	0.0	898
2032	0.0	0.0	85.0%	2,673	43.9	57	86,124	0.7	899
2033	0.0	0.0	85.0%	2,673	38.6	104	86,228	1.1	900
2034	0.0	0.0	85.0%	2,673	38.6	-	86,228	0.0	900
2035	0.0	0.0	85.0%	2,673	38.6	-	86,228	0.0	900
2036	0.0	0.0	85.0%	2,673	39.1	89	86,317	1.0	901

References

[A-1] "Integrated Data Base Report -- 1995: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics," DOE/RW-0006, Revision 12, U.S. Department of Energy, Washington, DC, December 1996.

[A-2] U.S. Department of Energy, "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Program," DOE/RW-0510, Washington, DC, December 1998.

[A-3] "Nuclear Power Generation and Fuel Cycle Requirements 1998," Table 9. Projected World Cumulative Spent Fuel Discharges, Reference Case, 1998-2020, Energy Information Administration, U.S. Department of Energy, Washington, DC, May 1998.

[A-4] O. W. Hermann, and C. V. Parks, "SAS2H: A Coupled One-Dimensional Depletion and Shielding Analysis Module," NUREG/CR-0200 Revision 6, Volume 1, Section S2, ORNL/NUREG/CSD-2/V1/R6, September 1998, Oak Ridge National Laboratory (Lockheed-Martin Energy Research Corporation).

[A-5] *SCALE 4.4—Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers*, CCC-545, September 1998, Oak Ridge National Laboratory (Lockheed-Martin Energy Research Corporation).

[A-6] N. M. Greene, et al., "The LAW Library A Multi-group Cross-Section Library for Use in Radioactive Waste Analysis Calculations," ORNL/TM-12370, Oak Ridge National Laboratory (Lockheed-Martin Energy Research Corporation).

APPENDIX B. TECHNOLOGY OPTIONS FOR ATW

This appendix summarizes some of the options for the accelerator and target/blanket-burner systems that are the components of accelerator-based systems for the transmutation of waste (ATW). In order to keep the scope and size of this appendix within reason, and to give appropriate credit, much of this summary is done by reference to previous work by others.

B.1 Accelerator Options

B.1.1 Linear Accelerators

In the case of the reference system shown in Section 4/Fig. 4-1, a linac is the optimal accelerator architecture. There has been a long history of successful operation of a high-powered linac at LANSCE. [B-1] It is a pulsed device operating at 0.8GeVwith an average beam power of 1 MW, a duty cycle of 10%, a repetition rate of 60 pulses per second, and an average beam current of 1.2 mA. Therefore the ~45-MW linac needed for the ATW program represents an extrapolation of ~ two orders of magnitude. Nevertheless several conceptual studies of such high-power linacs have been done with encouraging results.[B-2, B-3] The principal example is the accelerator designed for the Accelerator Production of Tritium (APT) program which is a superconducting device (a room-temperature option was also developed) with an energy of ~1 – 1.7GeV and a current of 100mA.[B-2] Extensive activities undertaken as part of the APT Engineering Development and Demonstration (ED&D) program are in the process of demonstrating the performance characteristics of key elements of the technologies required, including superconducting cavities, reliable performance of the ion source, and an integral test of the front-end of the system (Low Energy Demonstration Accelerator, LEDA).[B-2]

Because of the large amount of power involved, and the need for a high conversion efficiency, a superconducting cavity structure is the reference design for the ATW as well. This will allow a larger ratio of accelerator aperture to beam transverse cross-section, which is important to minimize beam losses and the consequences of component activation that would otherwise make operation and maintenance of the accelerator more difficult. Also, a larger accelerating gradient can be obtained with superconducting cavities, resulting in more compact devices ~200 m full length. The superconducting linac is ideal for continuous mode operation. It also allows flexibility on the selection of the final energy.

A description of the baseline linac is given in reference [B-3]. Several conceptual designs of superconducting linacs similar to that required for ATW have already been done at several institutions (e.g., LANL, BNL, CERN, INFN, ….) [B-2] and there is a high degree of confidence that an accelerator with the desired characteristics can be built, and will operate successfully. The major R&D required is in the area of reliability (i.e., ensuring highly reliable operation).

B.1.2. <u>Circular Accelerators</u>

Because they are pulsed accelerators with very low duty cycles, synchrotrons cannot be used for this application, since they cannot realistically generate the required average power. In contrast, circular accelerators that operate with a constant guiding field, namely cyclotrons and fixed-field alternating-gradient (FFAG) accelerators may be viable options.

A 1-MW cyclotron is already operating successfully at SINQ [B-4]. The final energy is 0.6 GeV with an average beam current of 1.6 mA. The operation is in a continuous-wave mode. Cyclotrons have also been proposed recently as the drivers for the “Energy Amplifier” concept [B-5]. Nevertheless, to generate the considerably higher beam power contemplated for ATW, several cyclotrons in cascade or in parallel are implied. To reduce the demand on the beam intensity a higher energy is desirable. While an energy of 2 GeV seems feasible, it is not clear how much beyond this one can go.

Injection in a cyclotron is limited to relatively low energy, thus causing significant limitations on the beam intensity due to space charge effects. The only way to cope with this is to let the beam increase in cross-section; this would require a considerably larger magnet gap. Another issue that needs to be investigated closely is the enhanced possibility of beam losses and therefore of consequent activation, when compared to a linac. Also, extraction is another area of concern. Since the beam is continuous, it may not be possible to allow for a “lossless” beam extraction.

A cyclotron is made of a compact core magnet which is divided into two sectors (“dees”). The pole face of the magnet is shaped to provide a variation in the field gradient for transverse focussing of the particle motion. The accelerating rf field is located between the two dees. The path length of the trajectories is determined to provide synchronous traversal of the radio frequency (rf) field. In contrast, the magnet of a FFAG accelerator is divided into sectors separated by drift tubes where rf cavities and other instrumentation can be located. Focussing in a FFAG accelerator is provided by either alternating the bending field, or by shaping the entrance and exit edges of the sectors. It is expected that FFAG accelerators are somewhat larger than cyclotrons for the same final energy.

FFAG accelerators have been demonstrated for the acceleration of electrons but never for protons. Nevertheless, acceleration of protons in FFAG accelerators has been proposed, and studied conceptually. The magnets of an FFAG accelerator have a crown shape with a considerable amount of empty space in the center. This makes it easier to inject at higher energies than are possible in a cyclotron. Consequently it is possible, in principle, to inject and accelerate more beam intensity. The injector in this case is a linac with an energy of several hundred MeV; the final energy can be in the few GeV range, up to ~5 GeV.

Cyclotrons and FFAG are more compact structures than linacs, and can be easily housed in more circular environments. Since the beam power is derived by going repetitively through the same rf accelerating system, it is not obvious that a superconducting magnet which does not accelerate would be that beneficial for this application. In any case, cyclotrons and FFAG have been shown to be very efficient when it comes to energy conversion.

B.1.3 Modular Approach

Several options for using modularity are possible. For example, the concept used in the reference design allows building a "shell" for the largest accelerator needed for a full demonstration. That shell would then be populated first with the minimum accelerator and incrementally with more accelerating and RF power equipment to upgrade it to its full power in a stepwise fashion. Since the equipment dominates the cost of the accelerator, this is a "modular" approach.

The smallest practical module consists of a single accelerator driving a single burner. Depending on the size of this module with respect to accelerator and burner requirements, such an approach may offer benefits in reducing technical risk, increased availability, etc. However, the degree of parsing is limited by the level beyond which the resultant overall system cost becomes greater than that of the current approach (i.e., cost-benefit). In addition, not all accelerator architectures are equally amenable to benefiting from increased modularization. In linacs where the rf accelerating system dominates all other considerations, some small number of linacs may be equivalent in terms of cost to a single linac with comparable beam power. By contrast, for circular machines the cost driver is the magnets and not the rf accelerating system; the cost of replicating these systems is therefore driven by the number of systems and not their individual beam powers.

B.1.4 Beam Conditioning

The proton beam that impinges on the target is in general modified from the basically Gaussian structure present in the accelerator. Two options that were considered for tailoring the transverse profile of the proton beam for the APT program were beam expansion via a system of magnets and rastering where the basically unmodified beam rapidly “painted” the face of the target; both approaches resulted in a basically uniform distribution on the window. A uniform distribution is generally desirable for mechanical (stress) and thermal (energy deposition and cooling) considerations to limit peaking.

B.1.5 Beam-Target Orientation

In the reference design the proton beam is assumed to be bent through an angle of 90 degrees and enters the target vertically from the top. Another option is to have the proton beam enter the target horizontally. There are benefits to each approach, and both have been employed/considered at operating and proposed spallation sources. The desirability/feasibility of each depends on the specific characteristics of the system; e.g., vertical injection makes the relative alignment of the accelerator and target-burner less crucial.

B.2 Target Options

The primary design objective of the spallation neutron producing target is to maximize usable neutrons produced per incident proton (n/p). The neutrons per proton depend on the target design but, for the targets under consideration, ranges from 25 to 30 neutrons/proton.

Differences in the geometric design of the target can cause greater differences in the production rate than differences in the materials being considered (W, Ta, Pb, Bi, Hg).[B-6]

A high production rate is not the only concern in maximizing the usable neutrons since the target material itself can absorb some of the neutrons. Another issue in producing *usable* neutrons is the spread of neutrons over the fuel axially. If the neutrons are produced over a short range there could be power peaking problems, and complicates cooling. If the neutrons are produced over too long of an axial distance there can be excessive axial leakage.

In an ATW the target converts about 10 MW of proton energy into neutrons. This is a large thermal load that must be managed. The following paragraphs will describe several approaches to maximize usable neutrons and manage the heat load.

The following target/coolant options have been considered:

- A solid target cooled by a dedicated coolant loop
- A solid target whose coolant is then also used as the “primary coolant” for the burner.
- A liquid metal target in an isolated loop
- A liquid metal target which then also serves as the “primary coolant” for the burner

The primary disadvantage of the second and fourth options is that the coolant/liquid target are in the proton beam, and hence will contain spallation products which would then be circulated into, and might adversely affect the integrity of the burner by interacting with the fuel cladding.

B.2.1 <u>PbBi Primary Coolant as the Target</u>

If PbBi is the primary coolant, the spallation target can be the primary coolant. The system only requires the proton drift vacuum tube to be placed down the center of the blanket and a metal cap to separate the vacuum from the primary coolant. The metal cap, called a window, takes a tremendous amount of radiation damage due to the protons crossing it and the neutrons returning back through it.

B.2.2 <u>Solid Target Options</u>

Tungsten (W) and Tantalum (Ta) are reasonable options for solid targets for ATW designs.
Other targets such as solid lead, uranium, and the other actinides are also possible, but may result in thermal issues.

Table B-1 shows some physical properties of tungsten and tantalum.

Table B-1. Physical Properties of Tungsten and Tantalum

	Tantalum	Tungsten
Atomic number	73	74
Density (gm/cc)	16.6	19.2
N (at/barn-cm)	.0553	.0632
Thermal neutron capture (barns)	21	19.2
Resonance Integral (barns)	660	352
Specific heat (J/kg-K)	0.14	0.14
Melting point (^{o}C)	3000	3410

The high capture cross section (thermal and resonance range neutrons) of both tungsten and tantalum indicate that targets using these materials will have significant parasitic absorption of neutrons. The target design should thus be configured as a high leakage arrangement, which ensures that the neutrons can leak into the surrounding blanket prior to capture in the target. Experimental data has been collected on the behavior of tungsten in high energy proton and neutron fields in support of the APT project.[B-11] A large operation base exists in the use of tantalum as a spallation target material for the pulsed neutron source at ISIS.[B-7] Both these data bases would be useful in designing a target for an ATW target based on one of these materials.

As noted above, the cooling for the solid targets can be done using a separate cooling loop or by also using it as the primary coolant for the burner. If sodium is the primary coolant, direct cooling of the solid target with the sodium primary coolant is possible. Direct cooling of the target with the primary coolant implies some spallation products will be in the primary coolant. In the case of sodium coolant the primary concern will be ^{7}Be which has a 53 day half life.

B.2.3 Isolated Liquid Target Options

Using a separate flow loop for a liquid target has the advantage of isolating the spallation products from the primary coolant. This would ease some of the chemistry control/corrosion concerns in the primary coolant loop for the burner, as well as the radiological impact of the spallation products. The flowing liquid metal target options, which can be considered for the ATW application, include lead, mercury, and lead/bismuth eutectic. Table B-2 shows the physical properties of interest for these materials.

Table B-2. Physical Properties of Liquid Targets

	Lead	Lead/Bismuth	Mercury
Atomic number	82	~ 82	80
Density (gm/cc)	11.34	~ 11.34	13.26
N (at/barn-cm)	0.033	~ 0.033	0.041
Thermal neutron capture (barns)	0.034	< 0.034	380
Resonance integral (barns)	~ 0.12	< 0.12	75
Specific heat (J/g-K)	0.155	0.147	0.137

The above table indicates that if a mercury target is chosen a high leakage configuration will have to be designed to minimize parasitic neutron losses in the target. Mercury also has a boiling point near the operating temperatures of the ATW system so care must be taken in the thermal design of the target. Lead and lead/bismuth targets would not require such complications, and this makes them more attractive candidates. However, the concern of liquid metal corrosion of structural materials in the presence of a proton and neutron radiation field needs to be addressed, since it could limit the choice of structural materials. Several studies [B-8, B-9] have been carried out in which the corrosion questions associated with Hg/Fe, Cr, Ni, Co, V, Cb, Ta, Ti, and Zr; and Bi-Pb/Fe,Ti,Zr, and Cu are discussed. The results published in these papers do not include the simultaneous exposure of the solid to the liquid metal and a radiation field. Selected experiments need to be carried out in which both the liquid metal and the appropriate radiation environment exist, before a final selection of structural materials is made. Finally, it should be noted that mercury is being proposed as the target for the next generation pulsed spallation source in both the U.S. [B-10] and Europe, [B-11] and a lead/bismuth eutectic is being proposed as the target for the SINQ. [B-12] These sources should be operational before the first ATW operates and thus experience gathered at these facilities would be of interest for ATW. The successful operational experience with Pb-Bi eutectic as a coolant for submarine reactors in the former Soviet Union provides an experience base for PbBi in a similar environment to that of the ATW burner.

B.2.4 Target Windows

The target window assembly separates the proton drift tube vacuum from the heavy metal neutron source target. In the case of the baseline design the heavy metal target is a lead-bismuth eutectic. The window is thus exposed to the full proton beam, and an intense flux of secondary radiation (neutrons, pions, gamma-rays etc.). It will therefore be subject to radiation damage by this radiation field, which will have energies well in excess of the fission and fusion reactor experience. Currently, the basis of most radiation damage experience is driven by requirements set by fission and fusion reactor designs. Several experimental programs have been undertaken in connection with the APT program, and in addition spent targets from spallation neutron sources have been examined.

The primary requirements for a spallation neutron source window design are that it must protect the accelerator, reliably survive for a practical time period before requiring replacement, and the replacement operation should be carried out completely remotely. The window size is determined by the beam footprint, which is determined by the primary proton radiation damage. Experience at various spallation source facilities has indicated that for water cooled windows operating at modest temperatures a beam current of approximately 80 mA/cm^2 results in acceptable window lifetimes (6 weeks at ESS).[B-11] Thus, knowing the beam current an acceptable window area and beam cross section at the window can be determined. In currently designed windows [LANSCE, SNS, ESS] the primary target containment is surrounded by a vacuum gap, which acts as a thermal insulator, and in addition it can be monitored for the presence of spallation products (indicating a leaking primary containment). The vacuum gap is enclosed in a double walled structure separated by a cooling water gap. Thus, the primary containment is cooled by the target cooling loop (mercury in the case of the SNS and ESS; lead/bismuth for the baseline design), while the secondary double walled structure is cooled by water. Finally, the window must be compatible with the target material (lead/bismuth) at the operating temperature over its lifetime.

A materials research and development program aimed at window materials and their behavior in an ATW needs to be included in the overall research and development effort. In addition to reactions between the lead/bismuth and the primary window, irradiation by fast neutrons and protons causes changes in the material properties due to atomic displacements, and generates hydrogen and helium gas. These damage mechanisms are unique to spallation sources, since they are caused simultaneously by both neutrons and protons, and experience from reactors does not apply. An experimental program should be started as soon as possible in order to develop the necessary data base to design a credible ATW window arrangement.

B.3 Target/Blanket (Sub-critical Burner) Options

In principle, any reactor design, reconfigured for source-driven subcritical operation, is a viable option for consideration as the sub-critical blanket/burner for an ATW system. The module can be directly irradiated by the proton beam (issue of proton damage, material performance in combined proton/neutron environment), or incorporated as a blanket region surrounding a spallation neutron producing target as is done in the reference design.

B.3.1 Burner Coolant Options

As noted in Section 3, the coolant for the burner can either be separate from, or integrated with that of the target. Selecting the coolant depends on a number of issues. They include thermal/mechanical, chemical, and nuclear characteristics. The thermal/mechanical characteristics include the heat capacity, density as a function of temperature, viscosity, and the phase change characteristics such as the melting and boiling points and the change in volume associated with a phase change. From these characteristics it is possible to infer the relative ease to find passive safety features such as natural convection cooling. The chemical feature of a coolant addresses issues of corrosion, toxicity, and energetic reactions (fires or explosions). The nuclear characteristics of a coolant are important to production of radioisotopes, use as a spallation source, and impact on the neutron spectrum.

In order to help compare some of the coolant options with regard to natural circulation potential Table B-3 has been developed.[B-13] This table shows PbBi has the best characteristics for natural circulation since the change in temperature results in the largest driving head and the second highest heat removal from this driving head. (Water properties provides twice the heat removal but a third of the driving head.) Finally, PbBi provides the most margin to boiling. Table 3-3 also has the Grashof number (ratio of bouyancy to viscosity) for the three liquid metals. The Grashof number shows that the PbBi eutectic is about 3 times that of pure lead or sodium (again implying PbBi will remove heat by natural convection easier than the other coolants.) Although PbBi has superior properties for natural convection cooling, this should not imply that natural convection cooling is not possible with the other coolants. Natural convection cooling is an important feature in passively cooled Na and water reactor designs. Table 3-1 merely suggests that less effort is needed to achieve natural convection cooling when using the PbBi coolant.

Table B-3. Comparison of Coolants for Natural Circulation

Coolant	Typical T_{in}/T_{out}	Driving Head ($\Delta\rho$)		Heat Capacity (ρc_p)		Margin to Boiling ($T_{boil}-T_{out}$)		Grashof number
		g/cm^3	Relative	J/m^{3}K 10^6	relative	C	relative	unitlessx 10^{14}
PbBi	340/510	0.205	1	1.53	1	1160	1	14.1
Pb	420/540	0.146	0.71	1.50	0.98	1185	1.02	4.8
Na	388/535	0.036	0.18	1.08	0.71	350	0.30	5.6
Water	283/325	0.073	0.36	2.93	1.91	18	0.02	

B.3.1.1 Lead-Bismuth (PbBi)

Lead-Bismuth forms a eutectic at 55.5 wt. % Bi and 45.5 wt. % Pb. The creation of the PbBi eutectic reduces the melting points from 327 C and 271 C for lead and bismuth respectively to 123.5 C. This coolant was selected due to a number of features. The PbBi thermal mechanical properties provide for a large operating temperature range (melts at 123.5 C and boils at 1670 C) so that guarding against boiling is easy. It is chemically inert so some accident concerns are reduced. PbBi is a good spallation source so the spallation target can be integral to the coolant. PbBi has been used in Russian reactors which allows strong cooperation with Russian nuclear scientists. For a review of the experience with PbBi reference (see reference B-14).

Some advantages of PbBi which are generally not important enough to influence the decision on coolant selection are:

- Low vapor pressure at operating conditions.
- High atomic weight results in a hard neutron spectrum and hence improved fission cross section for minor actinides as well as a higher neutrons per fission.
- Low capture, therefore good neutron economy (usable neutrons to drive the burner/subcritical blanket)
- Good neutron reflector and gamma shield.
- Retains most actinides and fission products if released into the coolant.
- Small volume change with solidification.

Of course, as with any option, there are some undesirable features of PbBi. The three primary concerns are its corrosiveness, its radioactivity after irradiation and its toxicity. PbBi can dissolve steels and can be contaminated by solid admixtures due to interactions with construction materials. This corrosive concern has been handled in Russia by the development of appropriate materials and the use of oxygen control to allow a protective oxide coat to form for protection of the materials. The oxygen control is sensitive since too much oxygen and too little oxygen can cause problems. The Russians have, through experience, solved this problem but the Russian systems did not have spallation products in the coolant. The Russians claim high confidence that this will not be a problem.

Bismuth plus a neutron creates ^{210}Po with a half-life of 138 days. This half life is short enough that it is not a waste concern but it is an operational concern. Fortunately, ^{210}Po stays in the PbBi coolant which self shields the ^{210}Po.

Lead and Bismuth are heavy metal poisons. They require adequate separation from the environment. When irradiated, they represent a “mixed” waste which further complicates disposal.

The PbBi coolant raises two cost concerns. First, the highly dense material leads to higher structural design costs and second, bismuth is relatively expensive (Bismuth costs about $3.50 per pound compared to around 20 cents per pound for lead or sodium. This is a few million dollars for all the coolant). Neither of these issues are significant when compared to the cost uncertainties in the current designs.

B.3.1.2 <u>Lead (Pb)</u>

Another coolant option would be to use molten lead. This would prevent the radiological hazards from ^{210}Po. The key disadvantages for lead are due to its high melting point (327 C). This higher temperature adds to the corrosion problems seen with lead-bismuth systems and it clearly requires more complex systems for maintaining and achieving the molten state. Other minor differences are that lead has a slightly lower spallation neutron yield than bismuth and lead coolant costs are lower by a few million dollars. A brief comparison of lead versus lead-bismuth can be found in reference B-15.

B.3.1.3 <u>Sodium (Na)</u>

Sodium does not have the corrosion concerns that exist with the reference PbBi coolant. Years of fast reactor experience have lead to high confidence in designs using a sodium coolant. However, PbBi has significant benefits over sodium due to its high margin to boiling and lower chemical reactivity with air and water. Further, sodium is not a good spallation neutron source so a separate target would be required. Clearly, ATW systems can be designed using sodium and there would be lower uncertainty in the system due to the experience base with sodium.

There are a few less important differences between the PbBi reference and sodium. Sodium melts at 98 C compared to 123.5 C. Sodium has a lower density so structural costs may be lower. The chemical and biological hazards (and disposal issues) of sodium are less than for

PbBi. The activation product ^{24}Na has a half life of 15 hours compared to $^{210's}Po$ half life of 138 days (however the self shielding of the PbBi helps mitigate the concern). Finally, the sodium coolant in the system costs a few million dollars less than the PbBi.

B.3.1.4 Helium (He)

Helium has a number of properties that make it desirable as a coolant for the ATW. Helium:

- Is chemically inert.
- Has no phase change.
- Is transparent to allow easier visual accesses to the fuel.
- Does not absorb neutrons. Hence it produces no radiological concern.
- Is non-corrosive.
- Allows direct use of a gas turbine for conversion to electricity.

The key undesirable feature is the high reliance on the pressure boundary. Normally, loss of pressure boundary concerns are compensated for by fuel with a high thermal inertia. There is a particular concern over the pressure boundary between the accelerator beam tube, which is maintained at a vacuum, and the primary coolant.

Reference B-16 provides information on how helium can be used in an ATW system.

B.3.1.5 Molten Salt

Molten salts can be used as a coolant. They have no advantage to be used just as a coolant but since the fuel can be mixed into the molten salt it has some distinct advantages. Molten salt ATW systems have been designed and discussion of molten salt is presented in the alternative systems section (3.8.1).

B.3.1.6 Water

Accelerator driven subcritical thermal systems tend to have problems with power peaking. This can be overcome by homogenous systems so the reactivity change with burnup is homogeneous. Aqueous fuel concepts could be used but none are currently being considered.

B.3.2 Blanket Fuel Options

This section will discuss some of the options related to the fuel. The reference ATW system selected is a metal cooled fast reactor. For this type of system traditional fuels are oxides and metals. There has also been a long-term interest in carbides and nitride fuels. Since ATW fuel will not contain large amounts of fertile material, the Doppler temperature feedback is small. A number of options for addressing this issue have been proposed for critical systems. Since higher k_{eff}'s reduce the accelerator power it may be desirable to investigate some of the Doppler feedback fuels so there is a subsection on this topic. Two fuel forms, molten salt and particle beds, are favored by some for ATW, although both are mentioned in this subsection most of the discussion is reserved for the section on alternate system designs.

B.3.2.1 Zr-metal

The selected reference fuel for ATW is vacuum cast, sodium bonded Zr metal fuel with between 10 and 25 wt% transuranic (TRU) material and 75 to 90 wt% Zr (approximately 5 to 13 atom percent TRU). The reference plan calls for half of the TRU to be fissioned which is around 3 to 7 atom percent of burnup. From a volume fraction of the fission products point of view this is equivalent to about a 30,000 to 70,000 MWD/MTU burnup. IFR demonstrated fuel burnups of 10 to 20 atom percent. Fuel testing is expected and options that could be explored include increasing or decreasing the Zr content of the fuel. Decreasing the TRU content will increase the thermal conductivity and melting point and hence add more thermal margin. Increasing the TRU content will decrease the number of fuel rods to be fabricated. Fig. B-1 is the phase diagram for the Zr-Pu system.

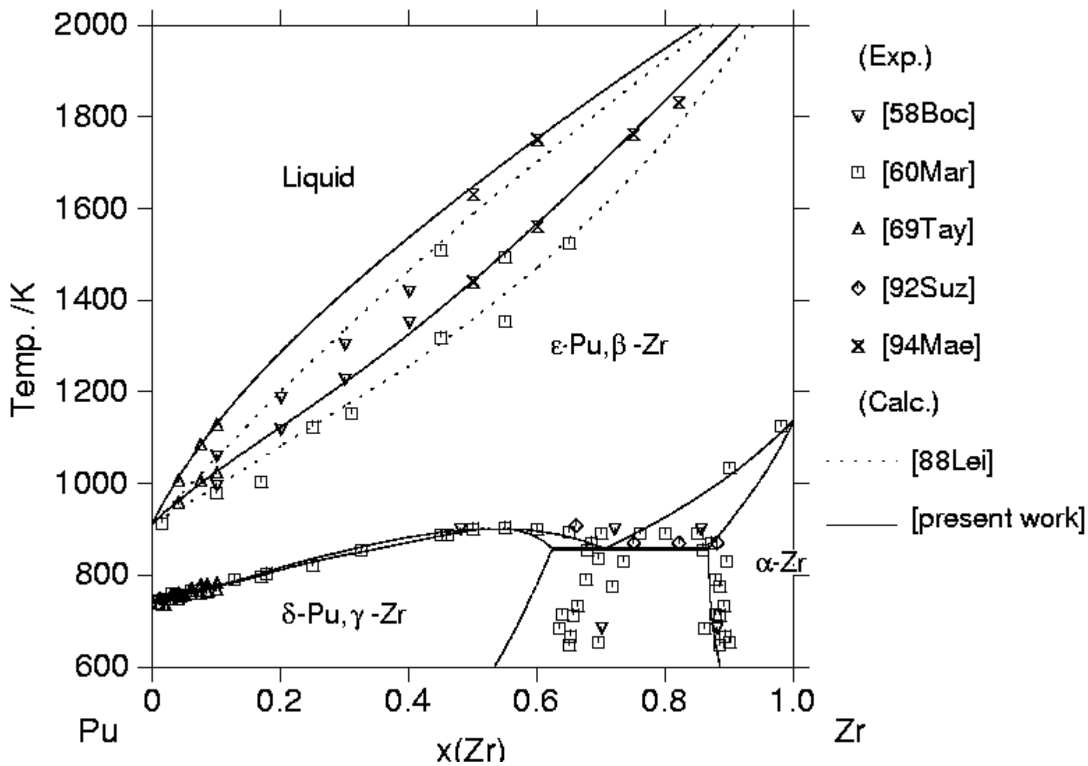


Fig. B-1. Pu/Zr Phase Diagram (Ref. B-21)

B.3.2.2 Nitrides

Nitride fuel has good thermal properties and can be used with pyrochemical processing. However, if the objective of the ATW is to burn all the tranuranics together, some method of dilution of the fissile material must be done to prevent criticality. In the reference case this is done by use of a low weight percent of TRU in the fuel. This could be done by making cermet fuels which are briefly mentioned in Section B.3.2.4. Traditional nitride fuels are being studied for use in burning just the minor actinides (MA) and using the plutonium in fast or thermal reactors. If the fuel cycle is changed to use an ATW for MAs then nitride fuels would be considered.

B.3.2.3 Enhanced Doppler Feedback Fuels

In transmutation applications, the ^{238}U is not present in the fuel. This is to prevent the creation of more TRU at the same time as it is being destroyed. The lack of ^{238}U reduces the Doppler temperature reactivity coefficient to near zero. Since the Doppler feedback is very important to the inherent safety of critical systems, some have concluded that a critical system without ^{238}U would not be safe. (Systems using highly enriched uranium have been operated extensively. These systems have very low Doppler feedback but have been designed to utilize other temperature feedbacks such as thermal expansion or moderator temperature feedbacks.) Analysis has been performed to design systems with Doppler feedback from isotopes other than ^{238}U. [B-18, B-19]

As a quick measure of how this can be done the resonance integrals of some materials are compared to that of ^{238}U on Table B-4. As can be seen on the table tungsten can provide Doppler feedback at a reasonable cost. Other elements such as Hafnium or Dysprosium, although costly, could be used as additives to enhance the Doppler feedback. With sufficient Doppler feedback ATW systems could be safely run at higher k_{eff}'s.

Table B-4. Resonance Integrals of Selected Elements

Element	Approximate Cost Per kg	Resonance Integral
U-238	$20	277
Thorium	$20	85
Tungsten	$0.05	350
Hafnium	$600	2000
Erbium	$600	740
Dysprosium	$300	1500
Gadolinium	$500	400

B.3.2.4 CERMET Fuels

Cermet fuels promise operational and safety advantages compared to oxide fuels, principally lower fuel temperatures, high geometric stability, and improved behavior on irradiation. These advantages stem primarily from the fact that the fuel “kernels” are in direct contact with, and “uniformly” dispersed within a metallic lattice, and the space between the cermet and the clad is filled with a metal alloy. Consequently, the heat transfer from the fuel to the coolant are enhanced, and the operating temperatures and thermal and mechanical stresses in the rod are reduced. Since fission products are retained within the fuel porosity and metal matrix, swelling/bowing are minimized, as is the potential for fission product release. These factors all contribute to enhanced safety. The possibility of pellet-clad interaction is eliminated, and clad corrosion is reduced, thereby allowing high burnups with attendant reductions in fuel-cycle costs and waste storage requirements. The experience base with fuels of this type for thermal or fast reactors, however, is limited.

B.3.2.5 Molten Salt

Molten salt fuels allow for the fuel to be dissolved in the coolant. This provides for a homogenous fuel where fuel can be added and removed continuously. This continuos operation changes the concern over changes in reactivity with burnup to one of correctly adjusting the feed and bleed operations. Correct operation of a molten salt reactor would sustain a constant amount of subcriticality, thereby avoiding burnable absorbers, control rods, or changing the accelerator power. The traditional first barrier to release of radionuclides, the solid fuel form, is non-existent in molten salt fuels, however, multiple barriers can be designed-in to compensate for this change in safety basis. Since molten salt reactors process the fuel continuously, the quantity of fission products in the fuel is reduced when compare to a solid fuel design.

Considerable work has been performed on a molten salt fueled ATW design and is discussed in Section 3.8.1.

B.3.2.6 Coated Particles

There are basically two types of particle fuel that have been considered/examined in the U.S.: sol-gel based graphite kernels, coated with silicon carbide, and developed by General Atomics into BISO/TRISO variants and utilized in High Temperature Gas Cooled Reactor (HTGR) fuel; and the Infiltrated Kernel (IK) approach developed by BNL in the SNTP program. [B-20]

Sol-gel was developed by the HTGR program, and has been demonstrated for uranium and plutonium carbides, oxides and oxy-carbides. Other actinides should be similar in principal, i.e., no problems.

The IK kernel was demonstrated for uranium but it is should be usable with other actinides because of similar chemistry. Other materials (e.g., fission products such as Tc or I, or burnable poisons) should be feasible provided a stable carbide form exists.

It has been demonstrated that sol-gel particles can survive high burnups (~100,000 MWD/T-AVR). For the IK kernel, high burnups are likely because of the internal porosity of the graphitic structure, and burnups of up to ~100% should be possible by suitable adjustment of the internal porosity.

All particle fuel should be coated to enhance fission product retention, and protect against reaction/erosion by the coolant. The choice of coating materials is based on compatibility with the kernel and coolant, and the level of burn-up desired (sol-gel). In general, silicon-carbide or metal-carbide are the materials of choice. A pyrolytic carbon intermediate layer is usually used between the kernel and coating for fission product retention, and to protect the outer coating for high burnups with the sol-gel based particles, and may also be desirable for IK.

The use of a “bare particle” geometry allows direct cooling of the particles; as a result, high power densities, hence high flux levels can be achieved. This ensures high burnup rates for the actinides and other fission products. It has been shown experimentally that power densities in the range of 5-6 MW/l (in the particle bed) are possible for particles whose outer diameter is ~500microns, and cooled by helium at ~1000psi (T_{he} ~1000K); at these conditions fluxes of $\sim 10^{16}$ n/cm^2-sec are achievable. Power densities of ~3MW/l have been demonstrated for water coolant at ambient conditions.[B-21] These characteristics, coupled with the graphitic structure of the particles allows a high operating temperature, and hence high outlet coolant temperatures if desired; if helium were used as the coolant a direct-cycle would be possible. The thermal margins in operating and accident scenarios are also high.

An example ATW design based on particle fuels is described in Section 3.8.2.

B.4 Fuel Processing Options

The technical details on fuel processing options are provided in "Part II: Technical Analysis and Systems Study" of the Separations Technology and Waste Form Technical Work Group Report (STWF TWG). The current reference approach is to perform aqueous processing on the commercial spent nuclear fuel at a single facility. Many aqueous options are discussed in the STWF TWG report. The aqueous options are preferred over pyrochemical techniques for the front-end since the fuel is cool (average time since discharge in excess of 20 years) and the volume of fuel to be processed is large.

The pyrochemical separation technique is the reference processing technique for the recycled ATW fuel since the volume is small and the expected cooling time is short. The pyrochemical separations are expected to be performed at the ATW sites.

B.5 Fission Product Burning Options

The reference ATW design will transmute ^{99}Tc and ^{129}I by absorption of a neutron. The design of the target material is under development but several issues can be addressed. ^{99}Tc plus a neutron becomes in the order of tens of seconds stable ^{100}Ru which has similar physical properties to ^{99}Tc. However, ^{129}I plus a neutron becomes ^{130}Xe in the order of tens of hours and ^{130}Xe is a noble gas. In the case of ^{99}Tc a target can be developed that will allow a very long residence time. In the case of ^{129}I pressure buildup is a concern which must be accounted for in the target design and could limit the target life. Another difference between the two fission products is their cross section. ^{99}Tc has a thermal absorption cross section of 20 barns and a resonance integral of 300 barns. ^{129}I has a thermal absorption cross section of 30 barns but a resonance integral of only 50 barns.

In order to help the transmutation of ^{99}Tc and ^{129}I, some moderation of the flux is useful. Unfortunately due to high thermal fission cross section of the TRU, thermalization of the neutrons can result in local power peaking problems.

It should be pointed out that one could consider not transmuting ^{99}Tc or ^{129}I but rather placing them in a long life container. The ^{99}Tc has a half-life of 213,000 years. Some have proposed that containers can be developed that can prevent ^{99}Tc from reaching humans before it decays. Unfortunately, ^{129}I has a 15,700,000 year half life and it is not believed that a container can be designed to last long enough to contain the ^{129}I however, gradual release of the ^{129}I over a long time frame would not exceed currently expected dose requirements.

B.6 Reactivity Control Options

As the fuel burns in the reference ATW design there is a change of reactivity. There are several options to compensate for this change in reactivity. The following is a list of some of the options:

1. Allow a decrease in power associated with the decrease reactivity.
2. Increase the accelerator beam power to compensate for the change in the reactivity.
3. Remove some absorber material to compensate for the change in reactivity.
4. Use frequent fuel shuffling and reloading to minimize the impact.

In all the cases the use of some type of burnable absorber is desirable. Burnable poisons that are effective in a fast spectrum need development.

In the reference design there is little change in reactivity with power so this reactivity would be covered by the at power subcriticality. If designs are made with significant reactivity changes with power then some control material would be needed for power changes.

B.7 Siting Options

In developing the ATW it may be desirable to co-locate all ATWs with one processing and fabrication plant. This would have security and proliferation advantages but would result in a very large energy park. The current ATW design produces 2490 MWe. The reference scenario suggests about 8 of these units. Under current electrical usage this would be far too much for one site. The number of sites may be important in institutional and cost analysis.

B.8 Summary

This appendix has reviewed a number of technical options for ATW designs. For more details it is recommended that the reader seek out the references and also review the reports of the other technical working groups. This appendix has demonstrated that should a problem arise with any of the options selected there are a number of alternatives available.

References

[B-1] Web Site: http://lansce.lanl.gov/.

[B-2] "APT Conceptual Design Report," LA-UR-97-1329, Los Alamos National Laboratory, April 15, 1997.

[B-3] "A Roadmap for Developing ATW Technology: Accelerator Technology," LA-UR 99-3225.

[B-4] G. S. Bauer, "SINQ as of 1998 – Status Report," 14th Meeting of the Collaboration on Advanced Neutron Sources, Starved Rock Lodge, Utica, IL. (1998).

[B-5] "Energy Amplifier Demonstration Facility Reference Configuration – Summary Report," EA B0.00 1 200-Rev. 0, ANSALDO, January 1999.

[B-6] G. J. Russell, E. J. Pitcher, and L. L. Daemen, 1995. "Introduction to Spallation Physics and Spallation-Target Design," LA-UR-95-817, Los Alamos National Laboratory.

[B-7] A. D. Taylor, and W. G. Williams, "Progress at ISIS," 14th Meeting of the Collaboration on Advanced Neutron Sources, Starved Rock Lodge, Utica, IL. (1998).

[B-8] J. R. Weeks, and A. J. Romano, "Liquidus Curves and Corrosion of Fe, Ti, Zr, and Cu in 500-750 C Mercury," Corrosion-NACE, Vol. 23, No. 4, April 1967.

[B-9] J. R. Weeks, and A. J. Romano, "Liquidus Curves and Corrosion of Fe, Ti, Zr, and Cu in Liquid Bi-Pb Alloys," Corrosion-NACE, Vol. 25, No. 3, March 1969.

[B-10] "National Spallation Neutron Source - Conceptual Design Report Vol. 2," The NSNS Collaboration, Oak Ridge National Laboratory, Oak Ridge, TN 37831. NSNS/CDR-2/V2 (May 1997).

[B-11] "The ESS Technical Study Vol. 3," J. Kjems ed. Risø National Laboratory, P O Box 49, DK-4000, Roskilde, Denmark, ESS-96-53-M (November 1996).

[B-12] G. S. Bauer, A. Dementyev, and E. Lehmann, "Target Options for SINQ - A Neutronic Assessment," 14th Meeting of the Collaboration on Advanced Neutron Sources, Starved Rock Lodge, Utica IL (June 1998).

[B-13] M. Kazimi, "Presentations from the International Accelerator Transmutation of Waste Workshop," Washington, DC, February 17-18, 1999.

[B-14] B. F. Gromov, et al. 1997 "Use of Lead-Bismuth Coolant in Nuclear Reactors and Accelerator-Driven Systems." Nuclear Engineering and Design, **173**, 207-217.

[B-15] H. Sekimoto, and Z. Su'ud, 1995. "Design Study of Lead- and Lead-Bismuth-Cooled Small Long Life Nuclear Power Reactors using Metallic and Nitride Fuel." Nuclear Technology, **109**, 307-313.

[B-16] A. M. Baxter, R. K. Lane, and R. Sherman. 1994. "Combining a gas turbine modular helium reactor and an accelerator and for near total destruction of weapons grade plutonium." AIP Conference Proceedings of the International Conference on Accelerator-Driven Transmutation Technologies and Applications, July 1994, Las Vegas, NV, 347-63.

[B-17] Web Site: http://cyberbuzz.gatech.edu/asm_tms/phase_diagrams/pd/pu_zr.gif.

[B-18] G. Chang, 1998. "Neutronic and Burnup Characteristics of an Actinide-Reduced Plutonium Fuel with Tungsten." Nuclear Technology, **122**, 43-51.

[B-19] J. M. Paratte, and R. Chawla,. 1995. "On the physics feasibility of LWR plutonium fuels without uranium." Annals of Nuclear Energy, **22**, 471-81.

[B-20] H. Ludewig, J. R. Powell, M. Todosow, G., M. Maise, R. Barletta, and D. G. Schweitzer, "Design of Particle Bed Reactors for the Space Nuclear Thermal Propulsion Program," Progress in Nuclear Energy, Vol. 30, No 1, pp 1-65, (1996).

[B-21] W. Katscher, Nuclear Technology, Vol. 53, p 557, (1977).

APPENDIX C. ATW REFERENCE PLANT PARAMETERS

The following table details the plant parameters used to predict the performance of the reference ATW plant.

Table C-1. Assumed and Computed Reference ATW Plant Parameters

Separations Facility

Parameter	Assumed or Input	Computed	Units
TRU loss fraction per pass	0.0010		
Fractional burnup per pass	0.3000		
Total processing loss	0.0033		
Tc & I processing loss	0.05		
Throughput- kgs of TRU/year		1765.8	kgs/yr
Throughput-kgs of Tc-99/yr		135.6	kgs/yr
Throughput-kgs of I/yr		37.9	kgs/yr
Throughput-Spent Fuel		169.2	tonnes/yr
Approximate Capital Cost	820.0*		$M
Annual Operating Costs	10.4%	85.3	$M

*1/9th of a $1500 M aqueous plant plus $100 M for pyro reprocessing

Accelerator

Parameter	Assumed or Input	Computed	Units
Proton Energy	1		GeV
Proton Current	90		mA
Number of beamlines	2		
Targets Supported	8		
Beam Power		90.0	MW
Power Required-Accelerator		304.0	MWe
Accelerator net efficiency		29.6	%
Power Required-Plant		378.6	MWe
Approx. Capital Cost per beamline	860		$M
Approx. Capital Cost for Accelerators		1720	$M
Annual Operating costs	2.5%	43	$M

Target/Blanket

Parameter	Assumed or Input	Computed	Units
$k_{effective}$	0.97		
nu (neutrons/fission)	2.95		
Neutron importance factor	1.2		
Spallation threshold	0.2		GeV
n/p multiplier-lead	33.8		
Energy per fission	208		MeV
Beam Energy Deposit fraction	0.7		
Burner Inlet Temperature	350		°C
Burner Outlet Temperature	500		°C
Thermodynamic efficiency	37.0		%
Operating fraction (capacity factor)	70.0		%
Atoms per kg of TRU	2.51e24		
Atoms per kg of Tc-99	6.08e24		
Atoms per kg of Iodine	4.71e24		
Tc conversion efficiency	0.7		
Iodine conversion efficiency	0.7		
Neutrons per proton		27.0	
Neutron multiplier		33.3	
Neutrons per second/target		7.60e19	
Fissions/second/target		2.50e19	
Fissions/year/target		5.52e26	
Neutron/fission for Tc		0.534	
Neutron/fission for Iodine		0.115	
Total neutrons/fission for Tc and I		0.649	
kg TRU fissioned/year/target		220.0	kg TRU/yr
kg TRU fissioned/year total		1760.0	
Fission heat		832.1	MWt
Target/blanket total heat		840.00	MWt
Electricity per target/blanket		310.8	MWe
Facility total electricity		2486.4	MWe
Auxiliary power		74.6	MWe
Net facility electricity capacity		2107.8	MWe
Net facility electric production		1474.8	MWe-yr/yr
Net plant efficiency		31.4%	
Electric production recirculated		52.2	MWe-yr/yr
Elect. prod. recirculated to accelerator		212.7	MWe-yr/yr
Total elect. production recirculated		264.9	MWe-yr/yr
Cost per target/blanket facility	257.5*		$M
Operating Cost per t/b facility	6.0%	15.5	$M

*includes BOP other than accelerator and pyro-processing

Facility

Parameter	Assumed or input	Computed	Units
Lifetime		60.0	years
Electricity market value (wholesale)		41.7*	$/MWe-hr
Total TRU fissioned		105.6	tonnes
Cost Summary			
Cost per target/blanket (per burner)	257.5[1]		$M
Operating Cost per t/b facility		15.5	$M
Accelerator Capital Cost	1720.0[2]		$M
Annual Operating costs		43.0	$M
Separations Capital Cost	820.0[3]		$M
Annual Operating Costs		85.3	$M
Total capital cost		4600.0	$M
Annual energy production		1474.8	MWe-yr/year
Annual energy production		12.9	TWe-hr/year
Electricity revenues		539.1	$M/yr
Spent fuel revenues		0.0	$M/yr
Waste disposal costs		2.4	$M/yr
Annual capital cost	6.0%	276.0	$M/yr
Annual operating cost	5.5%	251.9	$M/yr
Net operating revenue (cost)		8.8	$M/yr

*because the 8-burner, 2-beam ATW has been configured to provide highly reliable power for half the capacity, the wholesale value was calculated from long-term contracts at $49/MWe-hr for 50% of capacity and 1998 average spot market price of $25/MWe-hr for the remaining 20% of capacity.

[1] $175M/burner + $165M/pair BOP.
[2] $840M per 45 MW accelerator, includes BOP.
[3] ($2200M aqueous + $520M pyro A)/8.5 + $500M pyro B per ATW.

APPENDIX D. OVERALL ATW SCHEDULE

The schedule for the ATW project is provided as a preliminary identification of major activities and milestones. Fig. D-1 provides a Level One schedule. A more detailed schedule is provided in the ATW Overview Report. Based on a starting date of 10/1/99, sufficient R&D can be accomplished by early 2007 to provide firm design input to the accelerator/burner complex and to the fuel cycle complex to proceed with detailed plant designs (Title II) and procurement. Thus R&D will continue during the pilot plant demonstration work in existing facilities at several Government sites, while the design, procurement, licensing, construction and startup of the Demonstration Plant and the Fuel and Target Facility (FTF) is being accomplished.

The Demonstration Plant will operate at 30 MWth for 3 years, starting in 2016, followed by 2 years of operation at 420 MWth, to confirm the operation of the accelerator/burner complex and fuel and target performance. Fuel for these operations will be provided from the pilot plants. The Fuel and Target Facility will start up in 2017 and provide some initial fuel to the 420 MWth Demonstration Plant, and will recycle the Demonstration Plant fuel. By the end of the 420 MWth Demonstration Plant operation (2021), the ability to transmute the LWR spent fuel into waste forms that are acceptable to the high level waste repository at Yucca Mountain and to low level waste repositories will have been demonstrated.

As shown on Fig. D-2, the next step is to build an 840 MWth full size prototype of the final ATW plant. This Prototype Plant will be based on utilizing a full size core within the same vessel used for the 30 MWth and 420 MWth demonstration tests. The dump heat exchanger used for the 30 MWth and 420 MWth tests will be replaced with a full size steam generator and a full size 620 Mwe turbine generator which will be operated at 310 Mwe for the Prototype Plant. The full size accelerator (45 Ma) will operate at partial capacity (12 Ma) for the 30 MWth and 420 MWth demonstration tests, and will be upgraded to the full size 45 Ma unit for the prototype tests. A splitter and beam stops will be used to provide for full scale operation of the Prototype Plant. Fuel will be supplied from the Fuel and Target Facility (FTF) to permit initial fuel load in 2023, and subsequent recycle of the ATW fuel, and further supply of processed LWR fuel.

The 840 MWth Prototype Plant will have a two year startup period ending in 2025. A Prototype Test Report will be submitted to the NRC at that time as the last step in the process of obtaining an NRC Standard Plant Certification for an 8 burner 2480 Mwe plant, which is scheduled to be issued by 2027 (at the end of a two year full power period for the prototype plant). A Title I and Title II design and licensing effort for the Standard Plant will be completed in parallel with the design, licensing, procurement, construction and startup of the Demonstration and Prototype Plants. A PSAR and FSAR for the Standard Plant will be submitted to NRC. The NRC is also expected to be the licensing agency for the Demonstration Plant, the Prototype Plant, and the Fuel and Target Facility (FTF), with PSAR's and FSAR's required for each step. This early involvement with NRC should facilitate final NRC Standard Plant Certification for the 8 burner, 2480 Mwe plants. NRC licensing of DOE facilities is consistent with current government planning for future large projects.

NRC Standard Plant Certification will be a key event needed to privatize the construction and operation of n^{th}-of-a-kind (NOAK) full size plants. Seven NOAK plants with 8 burners, 2 accelerators, and a Fuel and Target Facility (FTF) on each of seven sites are envisioned, so the NRC Standard Plant Certification will provide the licensing basis for these plants, with separate PSAR and FSAR updates needed for each new site.

The approach of using a full scale prototype of a single reactor vessel and nuclear steam supply system (NSSS) as the basis for obtaining NRC Standard Plant Certification is the same approach used in the U.S. ALMR program, with the concurrence of NRC. Commercialization of the ALMR was to have followed immediately after receiving this certification. A Preliminary Safety Evaluation Report (PSER) was issued by NRC for the ALMR project, providing a good basis for the design of a sodium cooled burner system for ATW (with some areas potentially applicable to LBE coolant).

The support of the U.S. National Labs will be essential throughout all phases of the initial R&D effort to provide input to design and procurement, throughout the pilot plant demonstration phase and the prototype demonstration phase, throughout the startup and tests of all large scale plants, and throughout the interactions with NRC on the licensing process. This work will be required from the start of the project in FY 2000 to receipt of the NRC Standard Plant Certification in 2027. It is noted that this schedule also provides for continuity of the engineering and design staff for all phases of the FOAK plant (to completion of the 2480 Mwe Full Station). Continuity for the supply of major components has been provided to the fullest extent possible, based on the assumption that funding will be available to start the fabrication of some of these components prior to their need dates in the field to provide for continuity of work in the shops. This will permit cost savings for fabricated equipment as well as for the shop fabricated modules of the plants. All plants on the site will be constructed of shop fabricated modules to achieve the schedules shown in this report (and the associated costs).

The schedule is based on phased construction of facilities on the first Government site. This includes the following facilities shown of Fig. D-1:

	Fuel Load
Demonstration Plant, 30 Mwt/420 Mwt	2016/2019
Prototype Plant, 840 Mwt (310) MWe)	2023
FOAK Power Block, 2 x 840 Mwt (620 Mwe)	2027
FOAK ½ Station, 4 x 840 Mwt (1240 Mwe)	2030
FOAK Full Station, 8 x 840 Mwt (2480 Mwe)	2035/2036

The Fuel and Target Facility (FTF) on the site will begin operation on 2019 after a 2 year startup period. It will process all incoming LWR spent fuel in the UREX and Pyro A Sections of the FTF, and fabricate LWR-based fuel for the ATW. It will also process the irradiated ATW fuel in the Pyro B Section of the plant and fabricate recycled ATW fuel for return to the burner. All waste streams will be processed and packaged for offsite shipment to HLW and LLW repositories. Targets will be fabricated and recycled in the FTF. The FTF will be sized for 180 MTU/year, which is sufficient to process and fabricate fuel for initial core loads of all eight onsite burners due to the time available to meet initial fuel load dates. By keeping all functions of the FTF on the same site as the ATW burners, no offsite shipment of fuel material is required after receipt of the LWR spent fuel. This results in a highly proliferation resistant system. The details of the fuel processing fuel and target R&D, pilot plants, and support of the Fuel and Target Facility (FTF) are described in the relevant reports

Following receipt of the NRC Standard Plant Certification on 2027, the first privatized NOAK plant can be designed, licensed, constructed and receive fuel for the first two power blocks by 2037 (See NOAK Plant Schedule Fig. D-3), and for the second two power blocks by 2038, with full operation of each power block one year after fuel load. The 180 MTU Fuel and Target Facility will be constructed and started up in time to supply the fuel and targets on these dates.

The second NOAK plant is scheduled for fuel load on 2039 (power blocks 1 and 2) and 2040 (power blocks 3 and 4) at a separate site, with NOAK plants 3 to 7 scheduled to fuel load two power block every year so that the last two power blocks of the 7th NOAK plant has loaded fuel by 2050.

The overall ATW schedule (Fig. D-4) shows the operation of all eight plants (one FOAK and 7 NOAK plants) for 60 years to achieve the goal of transmuting all of the 86,000 MTU of commercial LWR spent fuel by 2110.

The ATW schedule is based on detailed schedules reviewed and concurred with by DOE on similar large projects (APT, ALMR, and MHTGR) and provides for realistic startup and operation dates of all facilities and the earliest credible completion of the mission. The schedule reflects the major constraints of a Programmatic EIS, site EIS's, permits (NESHAP, air, water, etc.), licensing (PSAR, FSAR), R&D data flow to design and procurement, procurement durations, engineering and plant operation data flow, fuel and target supply dates, and funding for all facilities.

The schedule risk is moderate since it is based on the R&D and design maturity of the APT accelerator and the ALMR plant design using sodium coolant, plus the IFR electrometallurgical process, the IFR metal fuel and U.S. aqueous processing experience. This schedule is based on the above reference design approach and would require revision if changes to LBE or other coolants were considered to be more advantages. The decision on the choice of coolants is scheduled for 2008 after sufficient R&D has been done on all the options, as discussed in other sections of Chapter 6.

ATW Project Coordination

An ATW Project Office will be established at the start of the project (Oct. 1999) to provide for administrative technical, cost, and schedule integration during all phases of the project. Technical and programmatic coordination of R&D tasks will be required to resolve the outstanding technical issues.

One of the initial task will consist of defining the overall technical guidelines for the project. This is crucial for its success.

The first mission will be to translate the broad goals of the project into clearly specified criteria, functional design requirements and R&D plans, and produce a top-level system definition; these criteria and requirements will evolve over time as results of the R&D tasks become available. Seven successive subtasks are planned:

- Project goals in terms of burning rates, waste form performance, cost, safety, proliferation potential, etc will be clearly reviewed and specified.
- Top-level trade studies will be performed to clearly identify and quantify the links between the various system parameters, and the sensitivities to major technical option modifications. These studies will concentrate on the choice of coolant, materials, fuel, plant design, plant size and throughput, target operating conditions, and chemical process recovery rates.
- These trade studies will also result in the definition of Functional Design Criteria, which will set objectives for the design and performance of the system components.
- Detailed trade studies will then be performed to obtain a preliminary optimization of the system. Certain of these trade studies have been identified by the various technical working groups; others cross the boundaries between the subgroups. A preliminary list of the important trade studies is provided in Section 6.4.1.
- Regulatory needs will be specified, taking into account existing knowledge, and feedback from interactions with the regulatory authorities.
- Functional Design Requirements (FDR) will be derived from these trades studies.
- R&D needs will be derived from the FDR taking into account the current status of the technologies, the relevance of technical improvements to meeting the Functional Design Criteria. A risk-based approach will be used to define R&D priorities.

The ATW project office will initiate the Environmental Impact Statement and the Siting Studies at its inception.

After this initial startup period, the ATW project office will:

- pursue the trade studies using feedback from the R&D programs and the operation of facilities, to help in system optimization;
- provide programmatic, technical and financial management;
- Coordinate the R&D tasks.
- Monitor the development of alternate options in international programs

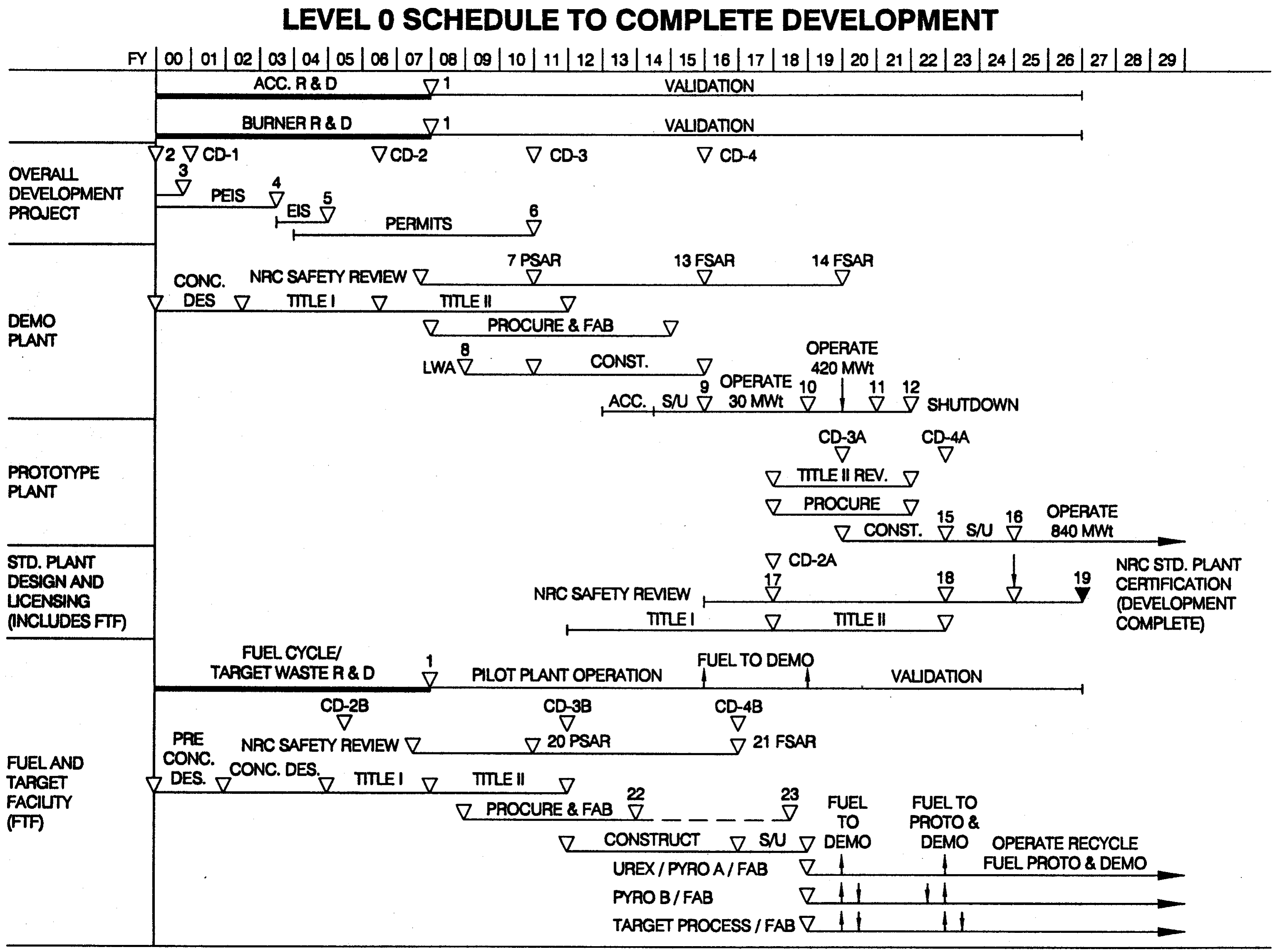


Fig. D-1. Level 0 Schedule to Complete Development.

Milestones for Level 0 Schedule to Complete Development

1. Decide final technology (1/2008)
2. Project Start (1/2000)
   - CD-1 Approve Mission need (1/2001)
   - CD-2 Approve Title [baseline, start Title II (Demo and Prototype (3/2006))
   - CD-3 Approve Construction (Demo) (1/2011)
   - CD-4 Approve Operation (Demo) (1/2016)
3. Mission Analysis/Need (10/2000)
4. R&D from PEIs, select site (3/2003)
5. Complete Facility/Site EIS (1/2005) all facilities
6. Complete Permit Approval (1/2011) all facilities
7. NRC Approve PSAR (1/2011), Demo, Prototype (1/2009)
8. Receive limited work authorization, start site work
9. Fuel load/start-up/operate at 30 Mwt (1/2016)
10. Fuel Load/Start-up/Operate up to 420 Mwt (1/2019)
11. Compete 420 Mwt tests (1/2021)
12. Shutdown, prepare for 840 Mwt (1/2022)
13. NRC approve FSAR (Demo and FTF) (1/2016)
14. NRC Approve update FSAR (Prototype) (1/2020)
    - CD-3A Approve Construction Prototype (1/2020)
    - CD-4A Approve Operation (Prototype) (1/2023)
15. Fuel Load/Start-up/Operate at 840 Mwt (1/2023)
16. Start Full Power Operation (1/2025) Proto test report to NRC.
    - CD-2A Approve Title I baseline, start Title II (STD Plant) (1/2018)
17. Start NRC review standard plant PSAR (1/2018)
18. Start NRC final review Std. Plant FSAR (1/2023)
19. NRC issue ATW Standard Plant Certification
    - CD-2B Approve Title I baseline, start Title II (FTF) (3/2006)
    - CD-3B Approve construction (FTF) (1/2012)
    - CD-4B Approve Operation (FTF) (1/2017)
20. NRC Approve PSAR (1/2011) FTF
21. NRC Approve FSAR (1/2017) FTF
22. Procure/Fab equipment for Proto/Demo Support (1/2014)
23. Procure/Fab equipment for FOAK Plant support (1/2019) as required

Fig. D-1. Level 0 Schedule to Complete Development (Contd.)

ATW PHASED CONFIGURATION AT FIRST GOVERNMENT SITE

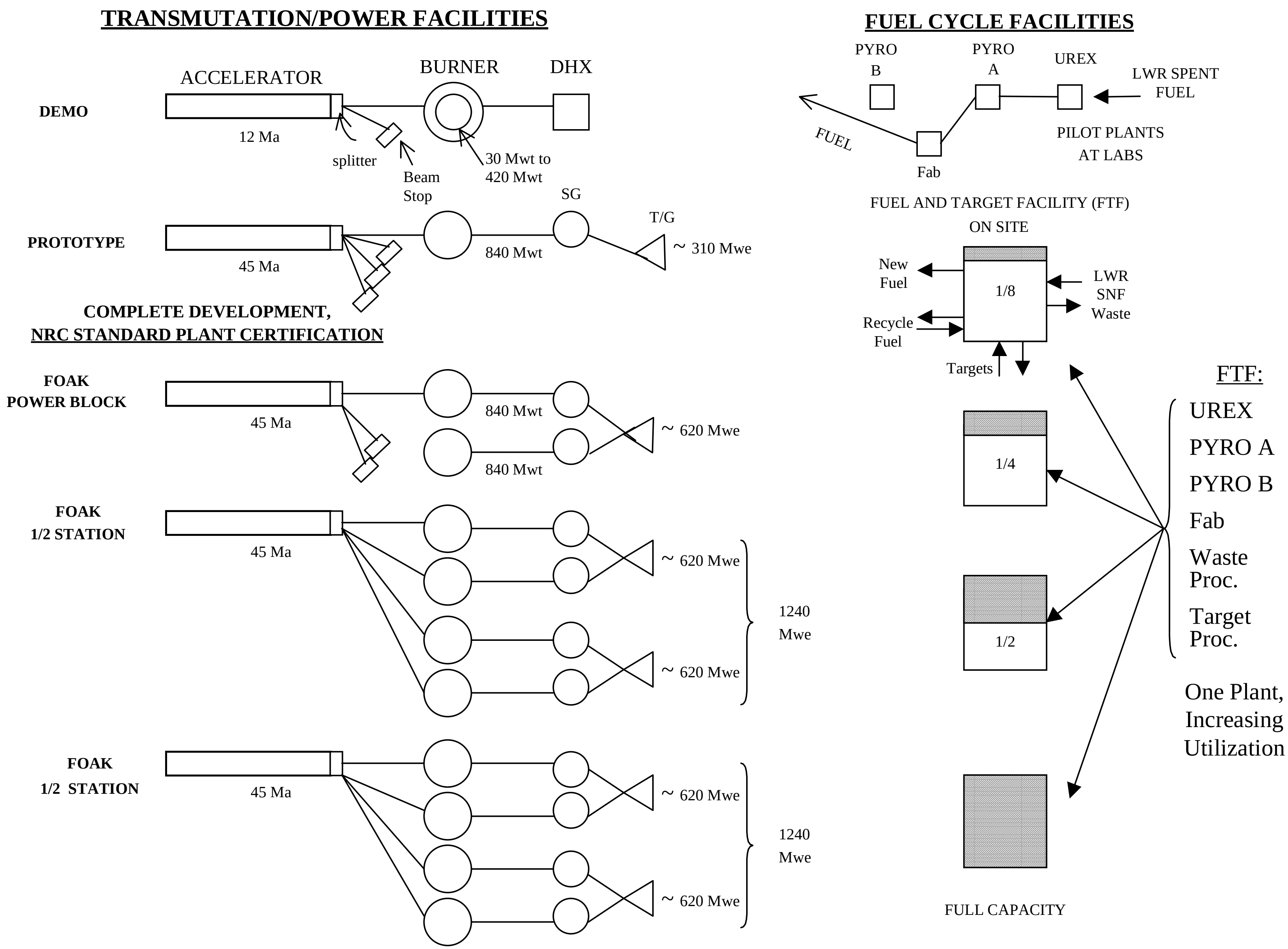


Fig. D-2. ATW Phased Configuration at First Government Site

ATW FULL CONFIGURATION
NOAK PLANT (2480 Mwe)
(Stations 2 to 8)

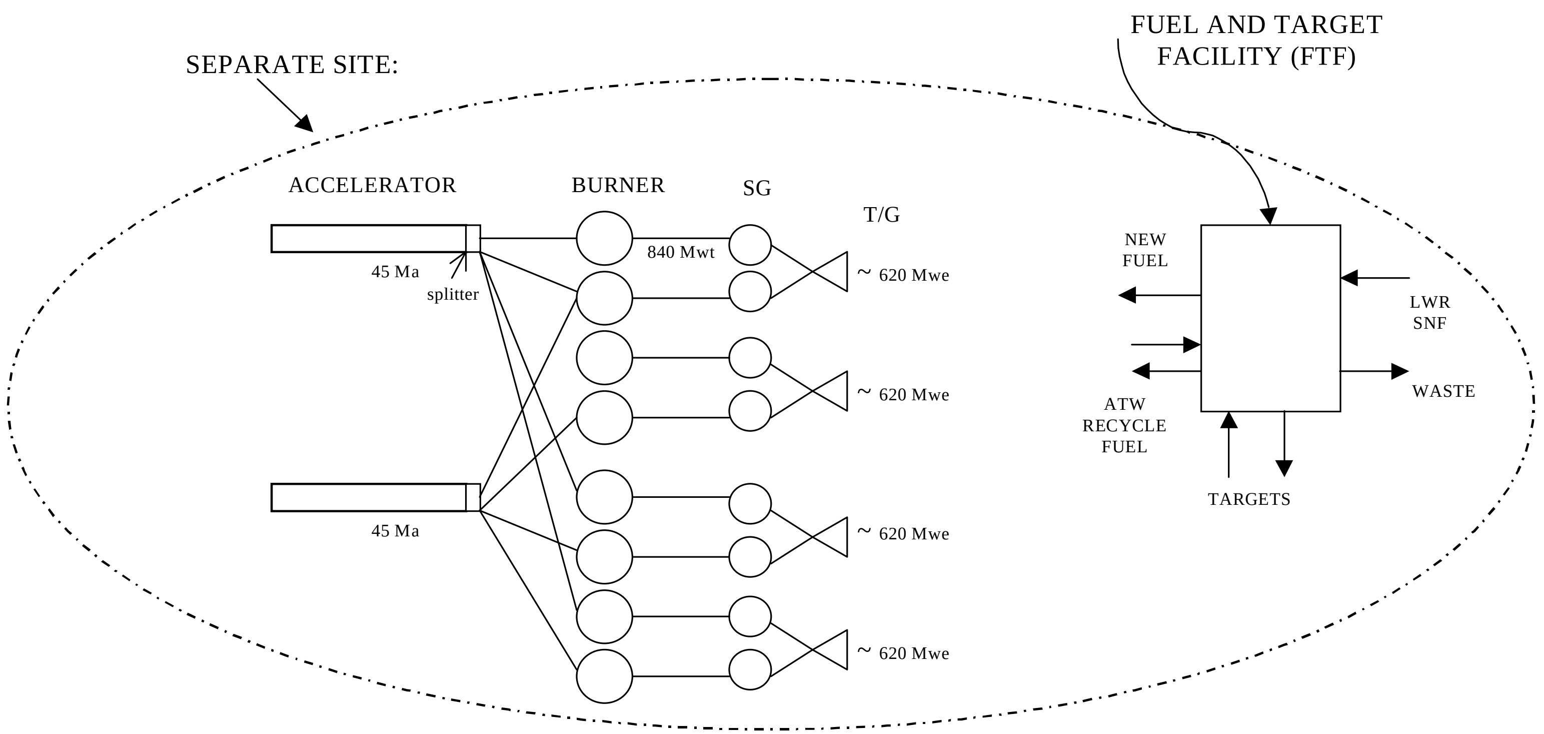


Fig. D-2. ATW Full Configuration NOAK Plant (Contd.)

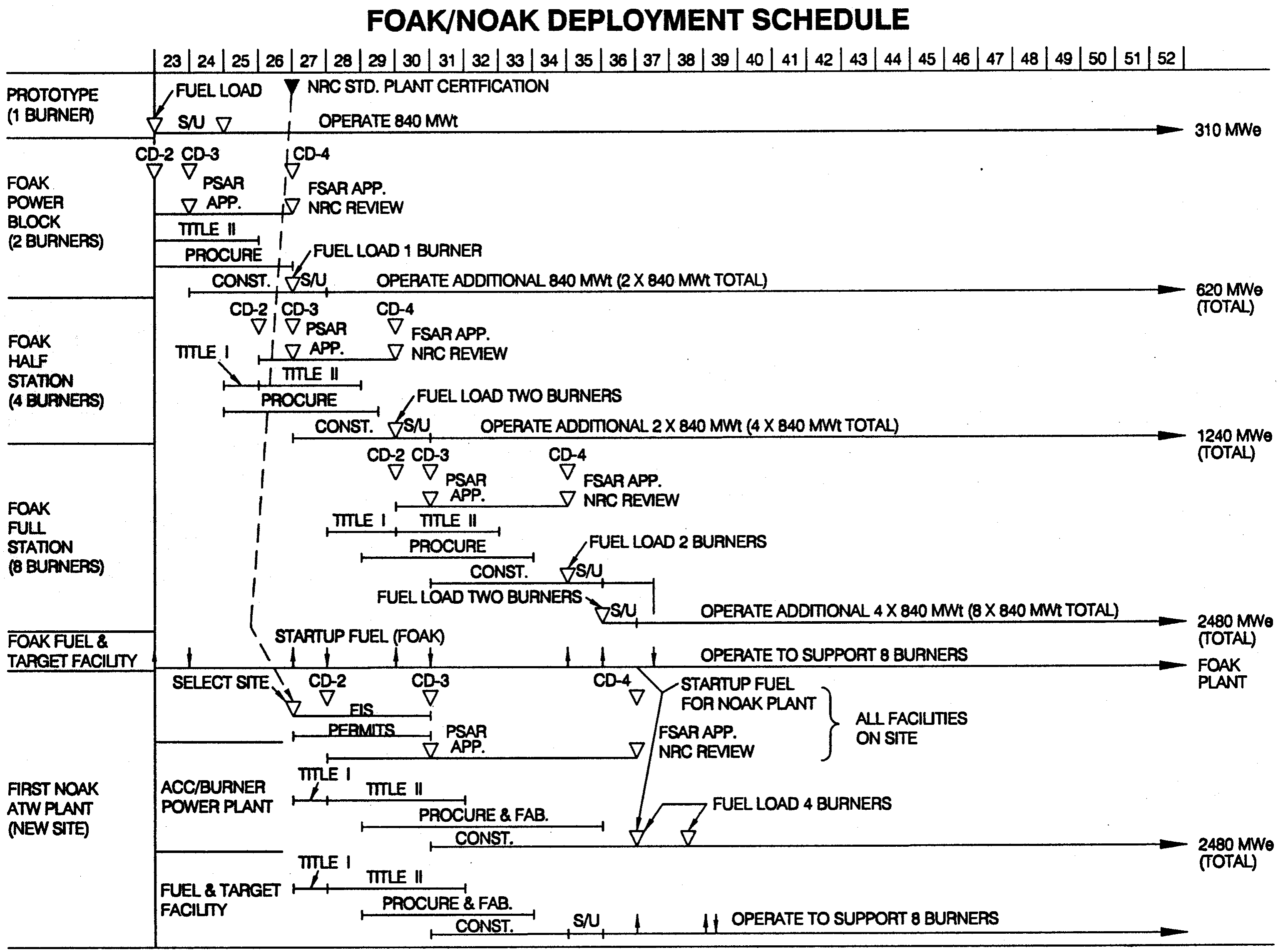


Fig. D-3. FOAK/NOAK Deployment Schedule

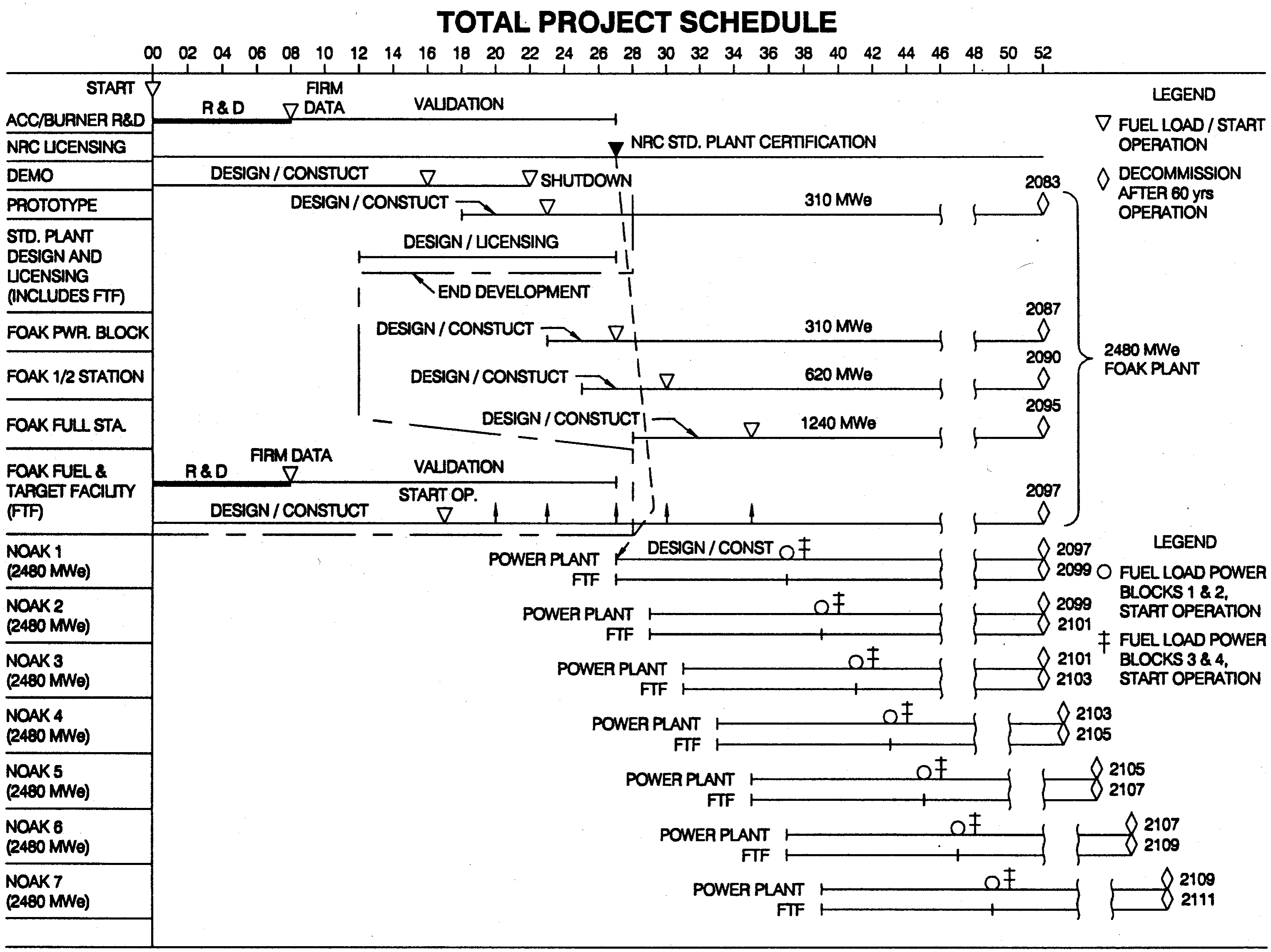


Fig. D-4. Total Project Schedule