PNNL-13018

Estimated Cost of an ATW System

October 1999

PNNL-13018

Estimated Cost of an ATW System

R. I. Smith
M. R. Shay
S. M. Short
C. S. Ehrman[(a)]
T. J. Myers[(b)]

October 1999

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

(a) Consultant
(b) Advanced Energy Systems, Inc.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

This document was printed on recycled paper.

Summary

A rapid deployment scenario and a possible schedule have been defined for performing the necessary research, development, demonstration (RD&D), and deployment of a system using high-energy proton accelerators to transmute long-lived radioactive transuranic elements into less hazardous materials and generate electricity as a byproduct (Accelerator Transmutation of Waste [ATW]). RD&D activities would begin in the year 2000 and be completed in 2027. Operation of full-sized production facilities would begin in 2028 and continue until about 2117 at a series of eight ATW stations that are put into service at approximately 2-year intervals, with each station operating for about 60 years. During this time, the expected inventory of commercial spent nuclear fuel would be treated through the ATW system.

The estimated life-cycle cost for the postulated ATW system is about $280 billion over a 117-year period and includes about $2 billion for R&D, about $9 billion for demonstration activities, and about $268 billion for system deployment and implementation. All costs are in undiscounted 1999 dollars. Revenue from the sale of the byproduct electricity could offset much of these costs, depending upon the sale price obtained for the electricity.

A Monte Carlo analysis of the uncertainties on the estimated system costs and a present-value analysis (assuming a 3% annual discount rate) of the expected system expenditures and revenues have been performed. These analyses show that there is less than a 10% probability the ATW electricity would be competitive with other commercial sources of electricity in a deregulated U.S. market, unless actual system operating costs are significantly lower than those estimated in this study.

Contents

Summary iii

1.0 Introduction 1.1

2.0 Summary and Conclusions 2.1

3.0 ATW System Scenario and Schedules 3.1

4.0 Estimated ATW Program Costs 4.1

4.1 Research and Development Costs 4.1

4.2 Demonstration Facility Costs 4.5

4.3 Full-Scale Deployed System Life-Cycle Costs 4.9

4.3.1 Methodology 4.10

4.3.2 Accelerator Base Costs 4.13

4.3.3 Transmuters 4.14

4.3.4 Separations and Recycle Facilities 4.16

4.3.5 ATW Fuel Fabrication 4.18

4.3.6 Site Support 4.20

4.3.7 Retrieval, Transport, and Disposal 4.20

4.4 Application of Adjustment Factors to Base Cost Estimates 4.22

4.4.1 Adjusted Accelerator Costs 4.22

4.4.2 Adjusted Transmuter Costs 4.23

4.4.3 Adjusted LWR Processing Costs 4.25

4.4.4 Adjusted ATW Processing Costs 4.26

4.4.5 Adjusted ATW Fuel Fabrication Costs 4.27

4.4.6 Adjusted Site Support Costs 4.28

4.5 Time Distribution of Total Program Costs and Revenues 4.28

4.5.1 Summary Displays of Undiscounted Costs and Revenue Streams 4.29

4.52 Net Present Value Analysis of System Costs and Revenues 4.31

5.0 Uncertainty Analysis 5.1

5.1 Methodology 5.1

5.2 Application of the Methodology to the System Components 5.2

5.3 Analysis Results 5.3

5.4 Production Costs for Investor-Owned Utilities 5.8

6.0 References 6.1

Appendix A - Historical DOE Construction Cost Escalation A.1

Appendix B - Application of Learning Curves to Cost Estimation B.1

Appendix C - Application of Scaling Factors to Cost Estimates C.1

Appendix D - ATW Program Development and Deployment Scenarios and Schedules D.1

Appendix E - Accelerator Development and Deployment Costs E.1

Appendix F - Transmuter/Power Facility Cost Bases F.1

Figures

2.1 Integrated Schedule for RD&D and Deployment of ATW Technology 2.1

2.2 Time Distribution of Undiscounted System Life Cycle Costs and Revenues 2.2

2.3 Percentages of Undiscounted Total Life-Cycle Costs, by Cost Element 2.2

2.4 System Cumulative Net Present Values of Costs and Revenues 2.3

3.1 ATW Program Phases 3.1

3.2 ATW Phased Configurations at the First ATW Station 3.2

3.3 ATW Full Configuration NOAK Station (2480 MWe) 3.3

3.4 Total Project Schedule 3.4

4.1 Total Target/Blanket (Transmuter) R&D Costs by Year 4.2

4.2 Total Accelerator R&D Costs by Year 4.3

4.3 Total Separations R&D Costs by Year 4.4

4.4 Total R&D Coordination Cost by Year 4.4

4.5 Total R&D Program Costs by Year 4.5

4.6 Total Target/Blanket (Transmuter) Demonstration Costs by Year 4.6

4.7 Total Accelerator Demonstration Costs by Year 4.7

4.8 Total Separations Demonstrations Cost by Year 4.8

4.9 Total Demonstration Integration Costs by Year 4.8

4.10 Total Demonstration Costs by Year 4.9

4.11 Simplified Schedules for Design, Construction, and Initial Operation of Stations 1 and 2 .... 4.12

4.12 Typical Undiscounted Station Capital Costs by Cost Element 4.29

4.13 Typical Undiscounted Station Operations Costs by Cost Element 4.30

4.14 Deployed System Undiscounted Costs by Cost Element 4.30

4.15 Time Distribution of Undiscounted System Life-Cycle Costs by Cost Element 4.31

4.16 Total Undiscounted System Costs with Electricity Revenues as a Function of Time 4.31

4.17 Total Undiscounted System Costs Minus Electricity Revenues as a Function of Time 4.32

4.18 System Cumulative Net Present Values of Costs and Revenues 4.33

5.1 Probability that Actual Accelerator Capital Costs Will Not Exceed the Estimated Cost 5.4

5.2 Probability that Actual Accelerator Operating Costs Will Not Exceed the Estimated Cost... 5.4

5.3 Probability that Actual System Capital Costs Will Not Exceed the Estimated Cost 5.5

5.4 Probability that Actual System Operating Costs Will Not Exceed the Estimated Cost..... 5.5

5.5 Probability that Actual System Implementation Costs Will Not Exceed the Estimated Cost..... 5.6

5.6 ATW Electricity Production Cost Probability Curve, Undiscounted, with RD&D Costs Included..... 5.6

5.7 ATW Electricity Production Cost Probability Curve, Undiscounted, with RD&D Costs Excluded 5.7

5.8 ATW Electricity Production Cost Probability Curve, Discounted, with RD&D Costs Included..... 5.7

5.9 ATW Electricity Production Cost Probability Curve, Discounted, with RD&D Costs Excluded 5.8

5.10 Comparison of ATW and Investor-Owned Utility Electricity Production Costs..... 5.9

Tables

2.1 Estimated Undiscounted and Discounted System Life-Cycle Costs, by Cost Element 2.3

4.1 Summary of Estimated Undiscounted ATW System Life-Cycle Costs 4.1

4.2 Total Target/Blanket R&D Costs 4.2

4.3 Total Accelerator R&D Costs 4.3

4.4 Total Separations R&D Costs 4.3

4.5 Total R&D Coordination Cost 4.4

4.6 Total R&D Program Costs 4.5

4.7 Total Target/Blanket Demonstration Costs 4.6

4.8 Total Accelerator Demonstration Costs 4.6

4.9 Total Separations Demonstration Costs 4.7

4.10 Total Demonstration Integration Costs 4.8

4.11 Total ATW Demonstration Costs 4.9

4.12 Estimated Base Costs for Elements of the Accelerator System 4.14

4.13 Estimated Base Design, Construction, D&D, and Operating Costs for Transmuters 4.15

4.14 Estimated Capacity and Base Costs for LWR Processing 4.16

4.15 Figures of Merit for LWR Processing Facilities 4.17

4.16 Capacity, Estimated Base Costs, and Figures of Merit for ATW Spent Fuel Processing and Recycle Functions 4.18

4.17 Estimated Capacity, Base Costs, and Figures of Merit for ATW Fuel Fabrication 4.19

4.18 Estimated Base Cost for Site-Support Functions 4.20

4.19 Effects of Adjustments to Accelerator Base Cost Estimates 4.23

4.20 Effects of Adjustments to Transmuter Base Cost Estimates 4.24

4.21 Effects of Adjustments to LWR Processing Base Cost Estimates 4.25

4.22 Effects of Adjustments to ATW Processing Base Cost Estimates 4.26

4.23 Effects of Adjustments to ATW Fuel Fabrication Base Cost Estimates 4.27

4.24 Effects of Adjustments to Site-Support Base Cost Estimates 4.28

4.25 Summary of Estimated Net Present Values of ATW System Life-Cycle Costs 4.32

1.0 Introduction

This report is one of six (ANL 1999a,b; LANL 1999a,b; PNNL 1999a,b) prepared in support of the U.S. Department of Energy's (DOE's) *Report to Congress* (DOE 1999), which was prepared in response to a congressional request that DOE study accelerator transmutation of waste (ATW) technology. Congress requested that DOE prepare a roadmap for ATW technology development, identify possible international collaborations, assess institutional challenges, consider possible impacts on the federal high-level waste repository program, and identify potential benefits arising from developing ATW technology. Congress also requested DOE to estimate the potential life-cycle capital and operating costs associated with developing and implementing a full-scale ATW system capable of treating the total inventory of civilian spent nuclear fuel. This report contains the estimated total system life-cycle costs (research and development (R&D), demonstration, and deployment phases) of a postulated ATW program, as requested by Congress. The major cost elements are identified and characterized for the purpose of estimating the programmatic cost associated with each of those elements. The estimates developed for R&D activities, demonstration facilities and activities, and capital and operating costs, and the electricity revenues for the deployed system are presented in Chapter 4 in constant January 1999 dollars. An analysis of the uncertainties associated with the estimated costs for each major cost element and the calculated probabilities that the actual total system costs will not exceed a certain amount are presented in Chapter 5. Selected information and methods supporting the analyses in Chapter 4 are presented in the appendixes.

The estimated life-cycle costs presented in this report are based on a scenario designed to develop and deploy an ATW system capable of satisfying its mission at the earliest reasonable time, i.e., a rapid-deployment or deployment-driven scenario. Much of the early R&D effort comprises conducting parallel investigations of system parameters, processes, etc., to obtain sufficient information to permit system design decisions to be made early enough to allow near-term deployment of the system. As a result, the first 5 years of the R&D activities in the deployment-driven scenario rapidly prepare for, and initiate, large component testing and process development in the hot cells, as discussed in the four Technical Working Groups' reports (ANL 1999a,b; LANL 1999a,b).

In contrast, the R&D program recommended in the *Report to Congress* is based on more narrowly focused goals that are expected to arise from the broad set of system studies to be performed during the first 2 years of the recommended program, and it is not under the time pressures of rapid deployment. The estimated R&D costs for the first 5 years of the recommended program are significantly smaller ($281 million) than the costs estimated for the first 5 years of the deployment-driven R&D program ($723 million) because the recommended program results are intended to provide only enough information to decide whether to proceed with further R&D and with ATW implementation. However, the deployment-driven R&D program was intended to produce sufficient information to permit start of system design and construction. As a result, the total system life-cycle costs for the more slowly developed ATW system (which have not been estimated) may be somewhat larger than for the rapid-deployment system due to the likelihood of an extended R&D period beyond the initial 5-year period and the attendant delays in deploying the revenue-producing ATW production stations.

The principal mission of the postulated ATW system is to destroy the long-lived hazardous transuranic elements present in the spent nuclear fuel (SNF) discharged from civilian light water reactor (LWR) power stations, thus reducing the environmental hazards associated with direct disposal of SNF in a geologic repository. A secondary mission may be to isolate and potentially destroy several long-lived and highly mobile fission products (technetium and iodine) present in the SNF. Completing these two missions would significantly reduce the magnitude of the radioactive dose to the environment over the very long times associated with releases of radioactivity from the geologic repository. An associated benefit is the generation of large quantities of electricity, whose sale would help defray the cost of performing the principal and secondary missions.

To accomplish the ATW missions, selected R&D must be completed, selected pilot plants and demonstration plants for the various processes performed within the ATW system must be built and operated, and the deployment of full-scale system elements must take place. The deployed system, as presently contemplated, would consist of eight ATW stations. Each station would consist of two large, high-energy accelerators and four power blocks (each block containing two sub-critical reactors [transmuters] and a turbine generator). The stations also would include a LWR spent fuel processing function, an ATW fuel fabrication function and an ATW spent fuel processing and recycle function, housed in a large common structure to facilitate transfer of the radioactive materials between the functions.

The accelerators provide a high-energy beam of protonsthat impinge upon spallation targets located at the center of each transmuter. This action generates the high-energy neutrons that transmute the transuranic elements by fissioning, yielding thermal energy which is used to drive the turbine generators.

The LWR spent fuel processing function separates the uranium, transuranics, and fission products present in the SNF; prepares the uranium for disposal as low-level waste (LLW); prepares the extracted transuranic elements for fabrication into ATW fuel assemblies; and treats and packages the separated fission products and the activated LWR fuel assembly hardware for disposal in the geologic repository. The ATW fuel fabrication function constructs fuel assemblies and target assemblies for the ATW transmuters using the separated transuranics and technetium and iodine from the LWR and ATW processing functions. The ATW spent fuel processing and recycle function processes spent ATW fuel and recycles the extracted transuranics back to the ATW fuel fabrication function where they are mixed with fresh transuranic feed material from the LWR processing function and fabricated into new ATW fuel assemblies. The extracted technetium and iodine materials are recycled into target assemblies to be irradiated in the transmuters, and the separated fission products and fuel assembly hardware are prepared for disposal.

It is postulated that the system would need eight production stations that would be brought into service at approximately 2-year intervals, with each station operating for 60 years, to consume the presently forecast inventory of civilian SNF (86,317 MTU-SNF, where MTU means Metric Tonnes of Initial Heavy Metal [i.e., uranium] in freshly fabricated power reactor fuel). Detailed schedules for deployment of the production system are presented in Chapter 3 and Appendix D of this reports.

2.0 Summary and Conclusions

A rapid deployment scenario and a possible schedule have been defined for performing the necessary research, development, demonstration (RD&D), and deployment of a system using high-energy proton accelerators to transmute long-lived radioactive transuranics into less hazardous materials and generate electric power as a byproduct (an ATW system). The schedule suggests that the RD&D activities would begin in the year 2000 and continue through 2027, with the efforts peaking in the 2010 to 2020 time period. The demonstration facilities for the accelerator, transmuter, and fuel processing facilities are sized to be upgraded to full-scale operational units and to form the bases for the initial power block at the first ATW station. The initial power production at the first station occurs in 2023 as part of the demonstration activities. As the demonstration efforts continue, the power level of the first transmuter is raised step-wise, reaching full power in 2023. The second transmuter is brought on-line in 2026 so that the first power block is complete and generating electricity. Following an additional year of operation of the first power block, the RD&D activities are complete. Power blocks 2, 3, and 4 of Station 1 are postulated to be commercial units, not financed by the government. They are postulated to come on-line in 2031, 2035, and 2036, respectively, completing Station 1. Commercial stations 2 through 8 are postulated to come on-line in rapid sequence, with power blocks 3 and 4 of Station 2 coming on-line in the same years as power blocks 1 and 2 of Station 3, and so on, until all stations are completed.

This rapid deployment scenario is illustrated in Figure 2.1, showing the schedule for RD&D and deployment. Also shown is the depletion of the LWR-SNF inventory at reactor stations and at the geologic repository, the cumulative electric energy generated, and the cumulative number of ATW repository waste packages in the repository over the system lifetime.

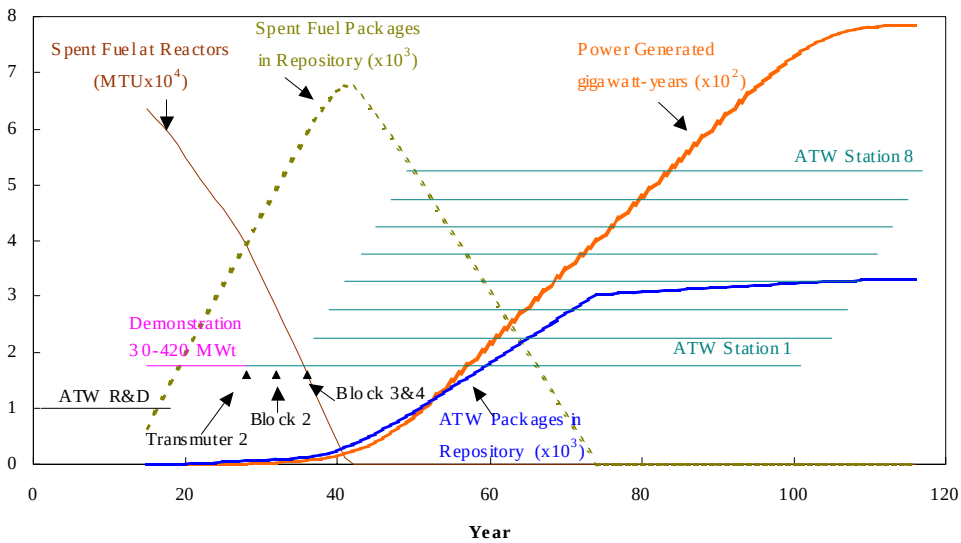


Figure 2.1. Integrated Schedule for RD&D and Deployment of ATW Technology

The time distribution of undiscounted annual expenditures to accomplish the postulated ATW deployment program is illustrated in Figure 2.2, together with the undiscounted electricity revenue calculated at an assumed rate of 43 mills/kWh This rate was suggested by the Electric Power Research Institute (EPRI) as being competitive with electricity generated in the United States using fossil energy.

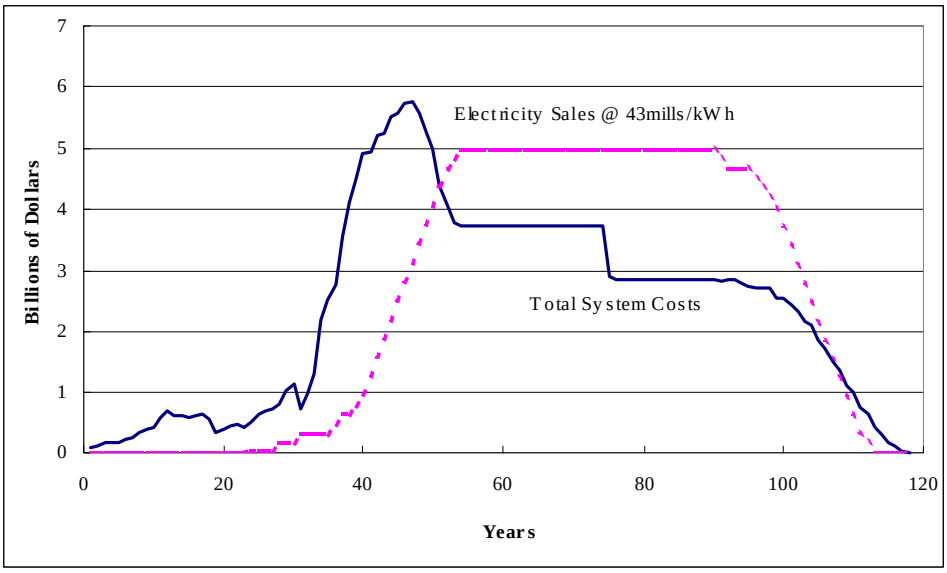


Figure 2.2. Time Distribution of Undiscounted System Life-Cycle Costs and Revenues

The percentage of undiscounted total system life-cycle costs assigned to the various system elements is illustrated in Figure 2.3. The cumulative undiscounted system life-cycle costs, including RD&D activities, is estimated to be $279.4 billion in 1999 dollars.

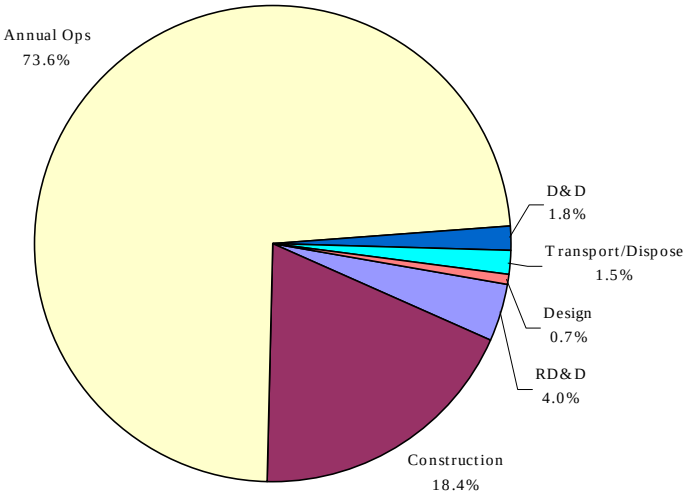


Figure 2.3. Percentages of Undiscounted Total Life-Cycle Costs, by Cost Element

However, the undiscounted costs and revenues presented above do not reflect the time value of money on these expenditures and incomes, which occur over a period of nearly 117 years. To properly evaluate the real economic effectiveness of a project that extends over a significant period of time, it is necessary to consider the time value of monies spent and received over the project lifetime, i.e., compute the net present values of those future costs and revenues. For this analysis, an annual net discount rate of 3% was used, assuming the 43 mills/kWh revenue rate mentioned earlier. The time distributions of the cumulative net present values of system costs and system revenues are shown in Figure 2.4.

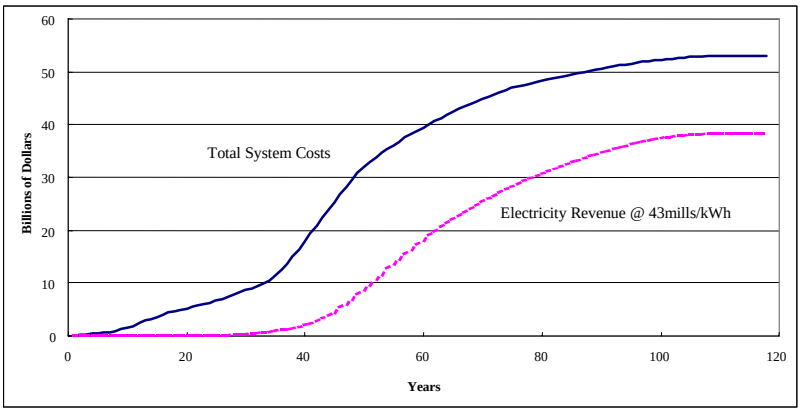


Figure 2.4. System Cumulative Net Present Values of Costs and Revenues

The undiscounted cumulative cost element expenditures and electricity revenues, summed over the system lifetime, are summarized in Table 2.1, together with the net present values of these same expenditures and revenues, calculated using a net 3% annual discount rate. The undiscounted net total system return, assuming the 43 mills/kWh sale value of electricity mentioned earlier, is +$15.5 billion dollars over the system lifetime. The discounted net present value of the total system return is -$14.8 billion dollars.

Table 2.1. Estimated Undiscounted and Discounted System Life-Cycle Costs, by Cost Element (billions of 1999 dollars)

System Cost Elements	Undiscounted	Discounted @ 3%
Research and Development	1.8	1.4
Demonstration	9.4	5.7
Post-Demonstration Capital Expenditures	53.5	16.1
Post-Demonstration Operations	209.8	29.7
Decontamination and Decommissioning	5.0	0.2
Total System Life Cycle Cost	279.4	53.1
Electricity Revenue	294.9	38.3

The estimated costs of the system elements assessed in this study are uncertain by varying amounts. Some cost estimates are based on similar concepts that have been extensively studied in previous DOE programs (e.g., the APT program for accelerators, the ALMR program for the reactors [transmuters]) and adapted to the ATW mission. Other estimates are based on limited engineering studies for similar proposed facilities, with limited or no actual experience base.

Because of the wide range of uncertainty on the individual components of system cost, a Monte Carlo analysis was performed to ascertain the probability that the actual system cost, if deployed, would not exceed the estimated cost. This analysis required assumptions about the range of uncertainty on each cost element and the independence of those uncertainties from each other. The results of this analysis showed that there is a 47% probability the actual system capital costs would not exceed the estimated cost, and that there is a better than 95% probability the actual system operating costs would not exceed the estimated system operating costs. This very high probability for not exceeding the estimated operating costs arises from not applying any learning curve adjustments to the operating cost input data, and suggests that the estimated operating costs used in the analysis over the system lifetime were too high. The combined results showed that there was a very high probability (nearly 95%) the actual total system implementation costs would not exceed the estimated system costs, a result driven by the high probability on the operating costs which compose nearly 74% of the total system costs.

The ability of the ATW system to produce electricity at rates competitive with other commercial sources of electric power is an important consideration when deciding whether to deploy such a system. As a part of the Monte Carlo analysis, the probability that the system could produce electric power at various rates was determined. Assuming a 3% annual discount rate on expenditure and revenue streams, it was found that there was only a 10% probability the system could produce electricity for less than 43.7 mills/kWh, and a 90% probability the power would cost less than 55.6 mills/kWh. This range of production costs is significantly higher than the 1996 production costs for most investor-owned utilities in the contiguous 48 states of the United States. If the 1996 production costs are typical of future investor-owned utility production costs, ATW electricity would be unlikely to be competitive with most of the electricity generated commercially in the United States.

The scenario and schedules evaluated in this report were developed for the purpose of estimating the approximate life-cycle costs of an ATW system. No attempt was made to fully optimize the system for the transmutation of commercial spent nuclear fuel material by considering other possible system configurations, (e.g., critical reactors versus subcritical transmuters, thermal neutron spectrum transmuters versus fast neutron spectrum transmuters, or an optimum system mixture thereof), nor was any consideration given to optimization of the overall spent fuel disposal system to reflect the inclusion of ATW technology.

3.0 ATW System Scenario and Schedules

The postulated system scenario and deployment schedule for the ATW system analyzed in this report are briefly summarized in this chapter, together with graphic illustrations of the schedule and the deployment scenario for the production portion of the system. Details of the postulated scenario and the development of these schedules are given in Appendix D.

The total system is proposed to begin with government funding and to be phased into a private funding and management system once the RD&D phases of the program are complete. The key phases of the program are shown in Figure 3.1 and are defined as follows:

- Government-Supported Phase (2000 to 2027)
  - -- R&D Phase (2000 to 2008)
  - -- R&D Follow-up Phase (2008 to 2027)
  - -- Demonstration Phase (2000 to 2027)

- Privatization Phase (2023 to 2117 or beyond)
  - -- FOAK (first-of-a-kind) Station Privatization (2023 to 2097)
  - -- NOAK (n^{th}-of-a-kind) Station Privatization (2027 to 2117)

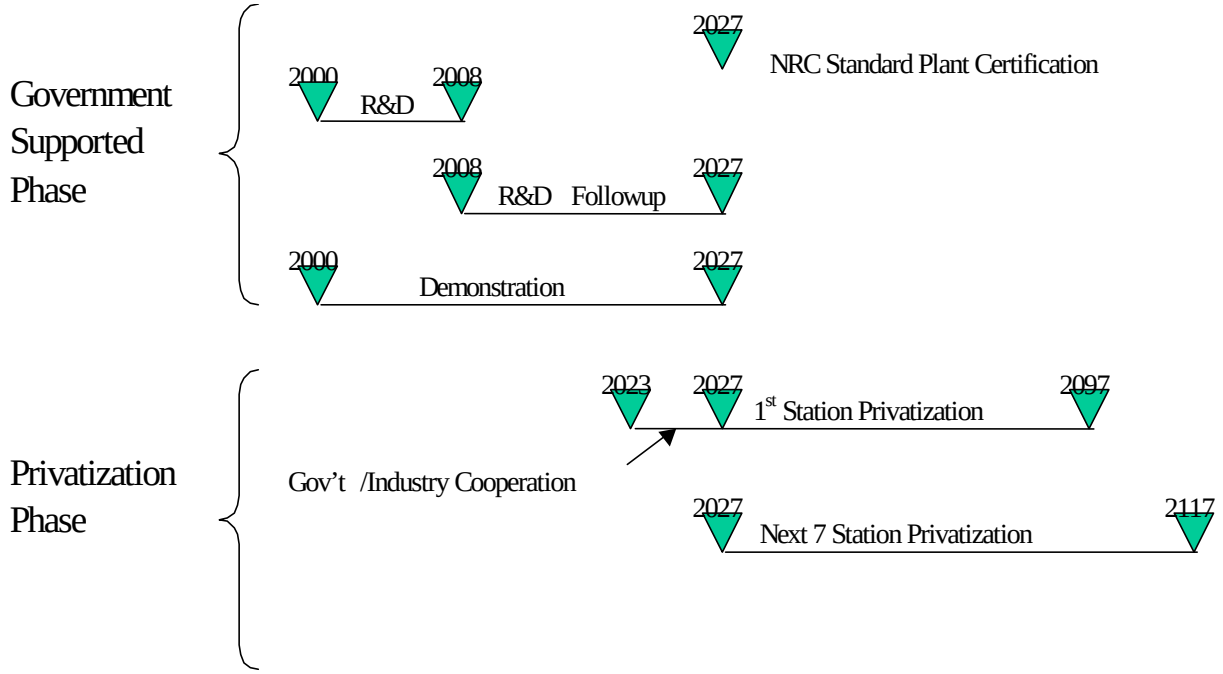


Figure 3.1. ATW Program Phases

The deployment scenarios for the first ATW station (part of which includes demonstration efforts) and for deployment of the subsequent production stations are illustrated in Figures 3.2. DEMO 1st PHASE illustrates the configuration for the start of the first accelerator and transmuter, where the heat generated in the transmuter is dissipated in a dump heat exchanger. Unneeded proton beam power is dissipated in a beam stop. Also during that first phase, some LWR fuel is processed, fuel for the first transmuter is prepared, and discharged ATW fuel is processed in hot cells at DOE's national laboratory facilities. DEMO 2nd PHASE illustrates the accelerator upgraded to full beam power, with one full-power transmuter, the addition of the steam generator and turbine-generator systems, and additional beam stops for the three beams not used. By this time, the fuel cycle facilities at Station 1 are operational at the level required to supply the first transmuter. FOAK POWER BLOCK 1 illustrates the addition of the second transmuter and its steam generator to the system creating the first complete power block, which is now using two of the four available accelerator beams, and is now producing about 620 MWe. The fuel cycle facilities are in full production, preparing fuel for the existing and for future transmuters. FOAK POWER BLOCK 1 and FOAK POWER BLOCK 2 illustrate the addition of the second power block to Station 1. NOAK POWER BLOCKS illustrate the addition of the second accelerator and power blocks 3 and 4 to Station 1, completing the construction for Station 1.

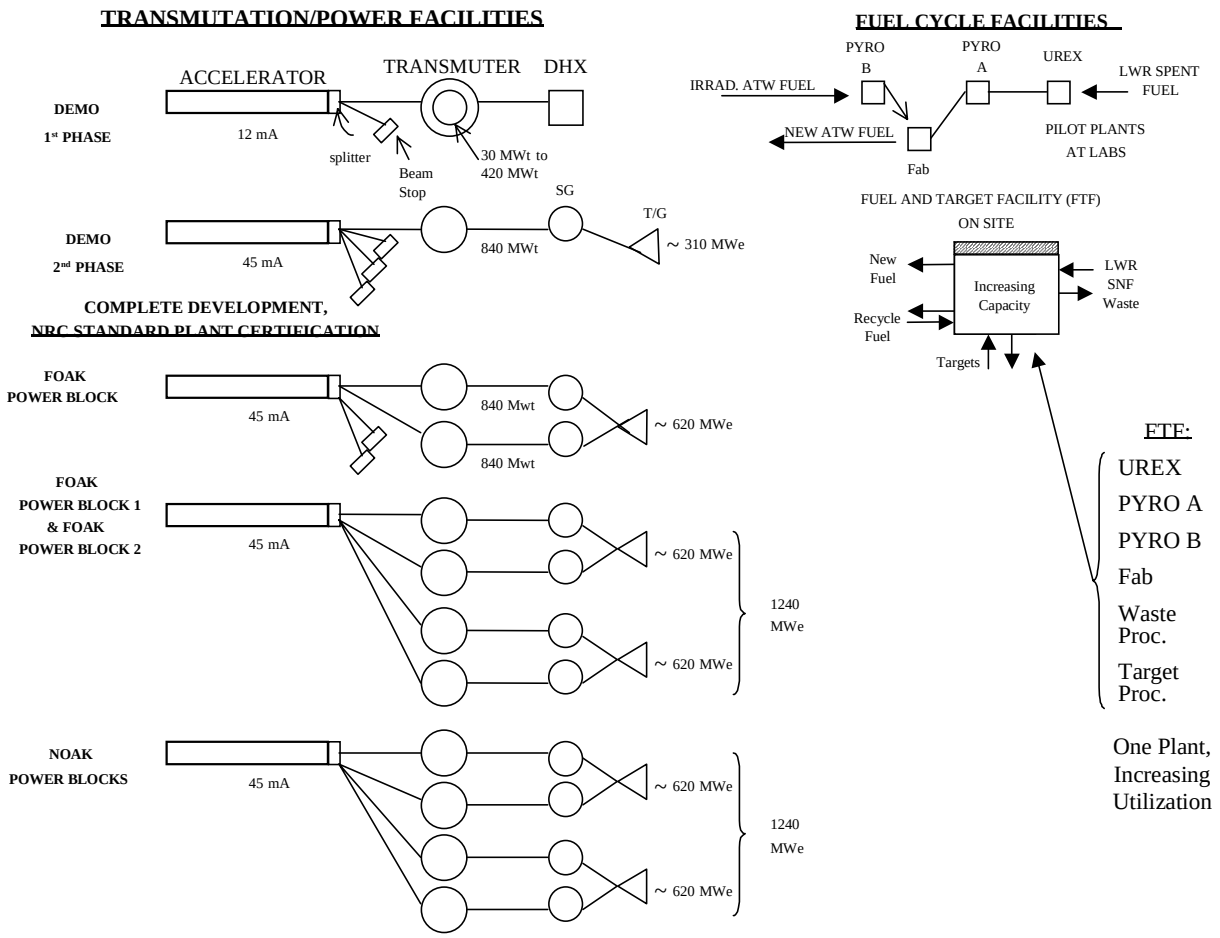


Figure 3.2. ATW Phased Configurations at the First ATW Station

The configuration of Station 2 and subsequent stations in the ATW system is shown in Figure 3.3. Each station is composed of two accelerators, eight transmuters, four turbine-generator systems, and the fuel cycle facilities and site support functions. Also shown are the interconnections between the accelerators and the transmuters, which are needed to avoid the loss of entire power block outputs when an accelerator shuts down. For the total system, it is postulated that no more than eight transmuters will be assembled on a single site, to keep the site power production within the range acceptable to major power distribution grids.

The postulated schedule for performing the necessary RD&D activities and for deployment of the operational production stations is shown in Figure 3.4. See Appendix D for more details on the bases and assumptions underlying these schedule arrangements.

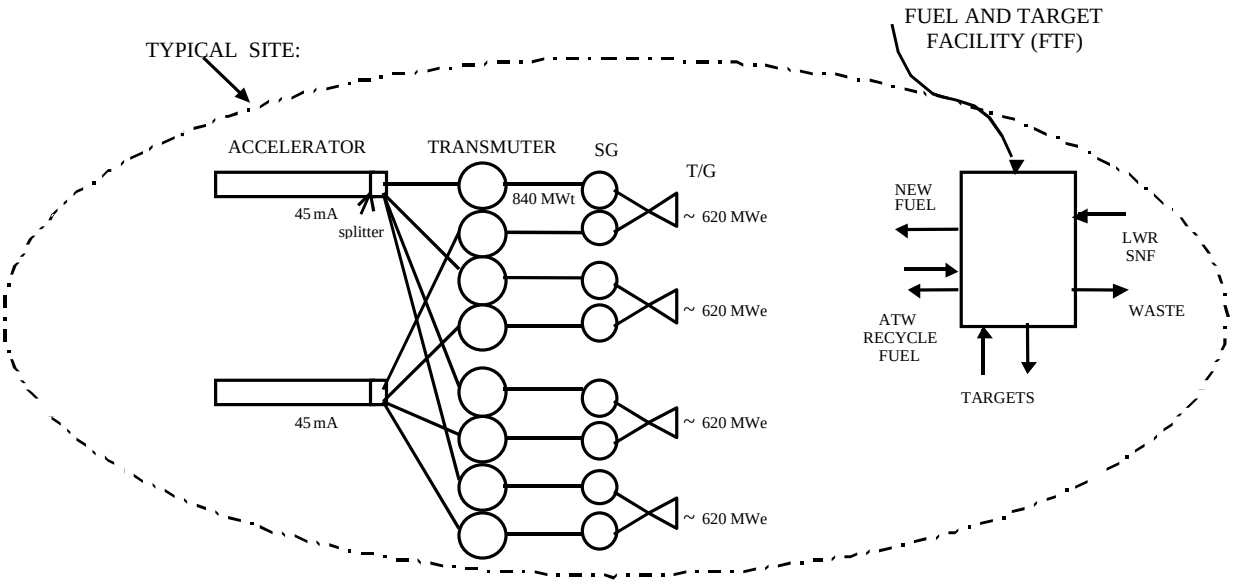


Figure 3.3. ATW Full Configuration NOAK Station (2480 MWe)

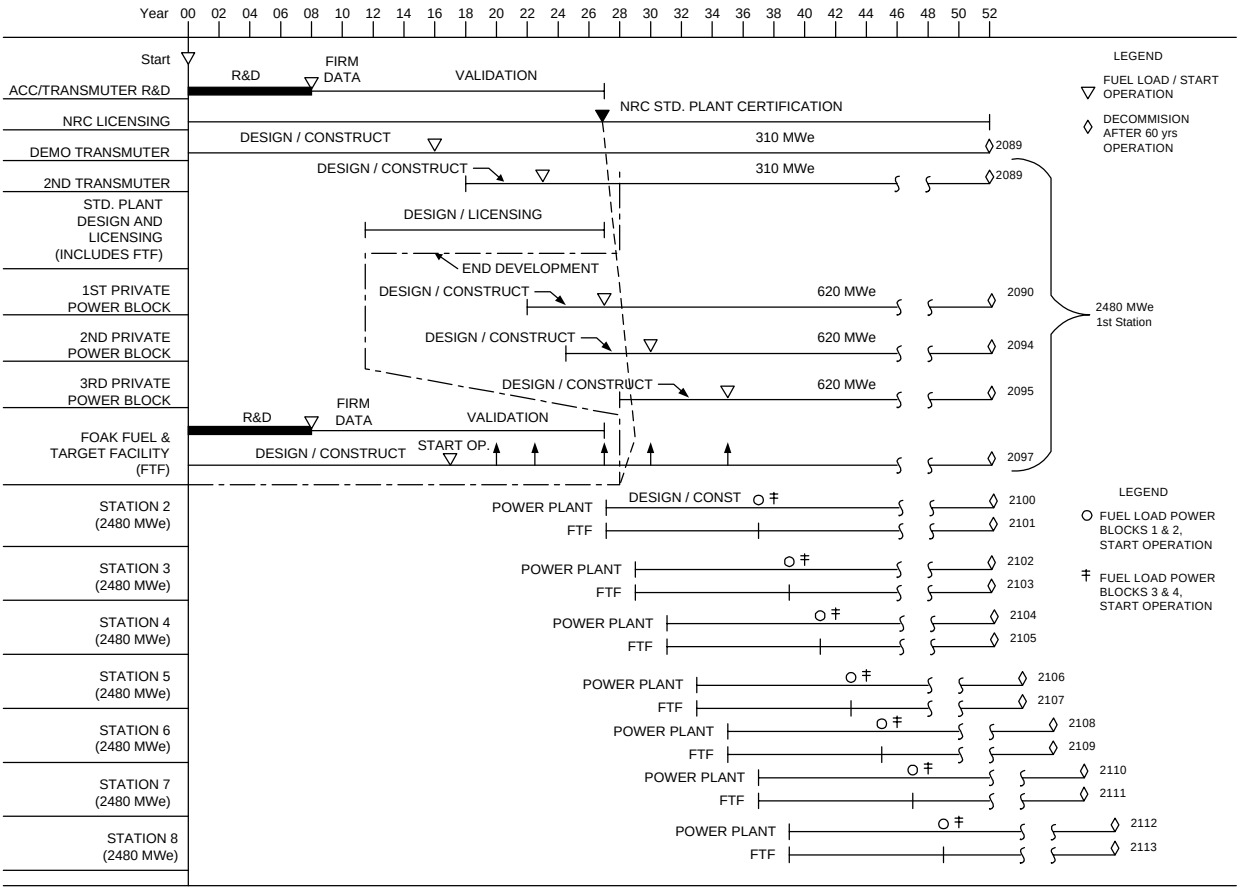


Figure 3.4. Total Project Schedule

4.0 Estimated ATW Program Costs

The estimated costs for the R&D program and pilot studies considered necessary for the rapid-deployment ATW system are briefly presented in Section 4.1. The estimated costs for the demonstration plant activities needed prior to full-scale system deployment are briefly presented in Section 4.2. The development of the estimated costs for the life cycle of the deployed ATW system is presented in Section 4.3 and its subsections. The effects of applying learning curve factors to the system capital cost components are presented in Section 4.4. The estimated total program costs and the distribution of those costs over the duration of the program are displayed and discussed in Section 4.5, together with the results of a net present-value analysis of the costs and revenue streams, assuming a 3% annual discount rate. All of these estimated costs for the postulated rapid deployment ATW system are summarized in Table 4.1 in undiscounted 1999 dollars.

Table 4.1. Summary of Estimated Undiscounted ATW System Life-Cycle Costs (billions of 1999 dollars)

System Element	R&D	Demo	Implementation			Total
			Capital	Operating	D&D	
Accelerators	0.17	2.5	11.2	44.4	0.6	58.8
Transmuters	1.03	2.1	30.2	49.4	3.1	85.8
Separations	0.50	2.2	9.0	40.5	1.0	53.3
ATW Fuel Fabrication	--	0.6	2.1	40.7	0.2	43.6
Site Support	--	1.0	1.0	30.6	0.1	32.7
Retrieval/Transportation/ Disposal	--	0.1	--	4.2	--	4.3
Integration	0.07	0.9	--	--	--	0.9
Subtotals	1.77	9.4	53.5	209.8	5.0	279.4

4.1 Research and Development Costs

The R&D programs and pilot studies that were developed by the Technical Working Groups (TWG) in the rapid deployment scenario for each of the principal technical areas are presented in detail in the individual TWG reports. The estimated costs and the distribution of those costs over time are repeated here for integration with the estimated deployment costs. The major technical areas examined are

- Target/Blanket (spallation target, fuel development, heat removal systems)
- Accelerators (beam switching, operational reliability)
- Separations (LWR aqueous processing, transuranic separations, ATW separations)
- System Integration (overall integration of the research programs).

The estimated costs for each of these technical areas are presented in the tables and figures of this section. The costs in the tables are separated into three time periods, to better illustrate the heavy

front-end loading of the R&D and pilot study efforts needed to obtain early information for facility designs, which begin as early as 2005. The annual costs in each technical area are shown in the figures, separated into the principal sub-parts of that technical area.

Spallation target assemblies would be tested using high-energy protons from the Los Alamos Neutron Science Center (LANSCE) accelerator at Los Alamos National Laboratory to demonstrate neutron yields and dispersion for different target materials and to demonstrate target cooling technology.

Pilot-scale fuel development for ATW would be performed initially in existing hot cells at Argonne National Laboratory-West (ANL-W), with test fuel irradiated in available fast reactors. Initial fuel for the 30 MWt, 420 MWt, and 840 MWt loadings in the first transmuter will be fabricated in the hot cell pilot fuel preparation facilities. Fuel for subsequent loadings will be fabricated in the Fuel and Target Facility at Station 1. Some demonstration effort is expected in the heat removal area.

The aqueous and pyrometallurgical methods for spent fuel processing would be performed at pilot scale in existing hot cell facilities at ANL-W and at the demonstration level in the first full-sized facility, which would be constructed at the site of the first ATW station.

The total Target/Blanket (transmuter) R&D costs are summarized in Table 4.2 by cost element. The time distribution of these costs over the R&D phase of the program are illustrated in Figure 4.1, also by cost element.

Table 4.2. Total Target/Blanket R&D Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Blanket Technology	153	35	0	188
LBE Coolant Technology	48	32	86	166
Target Technology	22	3	4	30
Sodium Technology	115	133	244	492
Nuclear Design & Safety	49	23	82	154
Total	387	226	416	1030

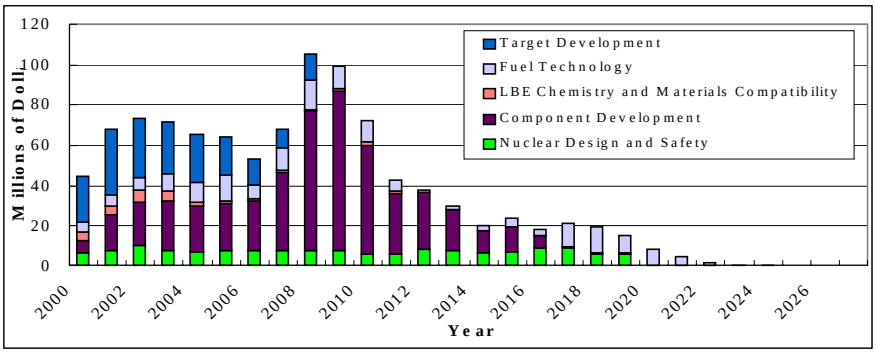


Figure 4.1. Total Target/Blanket (Transmuter) R&D Costs by Year

The total Accelerator R&D costs are summarized in Table 4.3 by cost element. The time distribution of these costs over the R&D phase of the program is illustrated in Figure 4.2, also by cost element.

Table 4.3. Total Accelerator R&D Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
LEDA Operations	38	0	0	38
Splitters Development	10	6	0	16
Reliability Improvement	18	8	6	32
RF Components	20	8	5	33
LINAC Components	29	6	12	47
Total	114	28	23	165

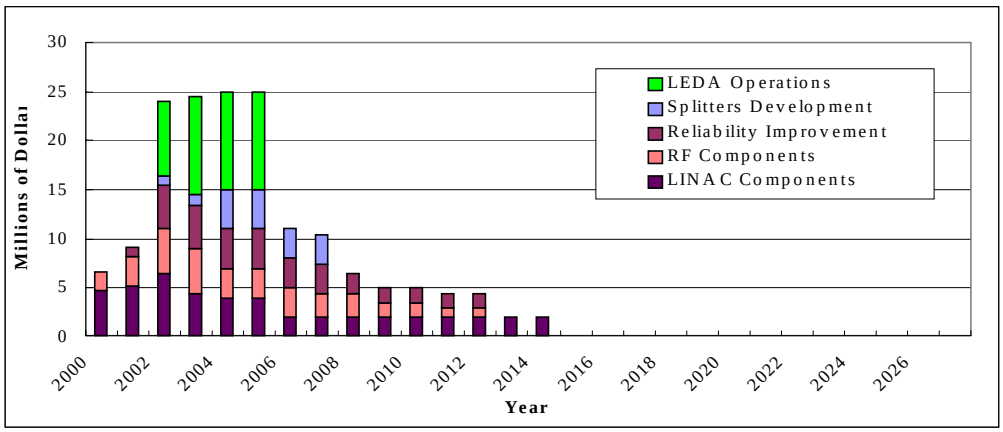


Figure 4.2. Total Accelerator R&D Costs by Year

The total Separations R&D costs are summarized in Table 4.4 by cost element. The time distribution of these costs over the R&D phase of the program is illustrated in Figure 4.3, also by cost element.

Table 4.4. Total Separations R&D Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Waste Forms	42	17	28	87
ATW Fuel Processing	79	38	113	230
LWR Fuel Treatment	68	26	88	182
Total	189	80	229	498

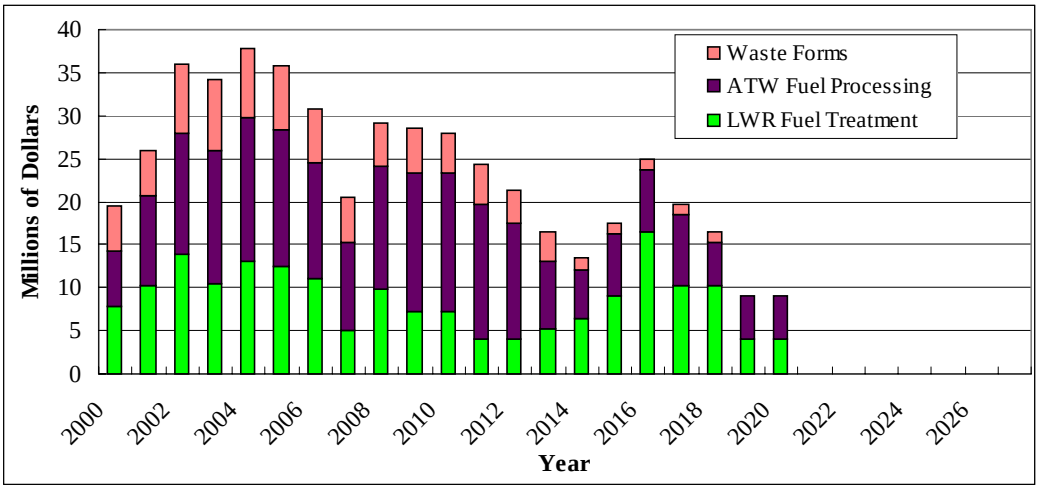


Figure 4.3. Total Separations R&D Costs by Year

The total Coordination R&D costs are summarized in Table 4.5 by cost element. The time distribution of these costs over the R&D phase of the program is illustrated in Figure 4.4, also by cost element.

Table 4.5. Total R&D Coordination Cost
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Coordination	15	9	28	52
System Studies	18	4	0	22
Total	33	13	28	74

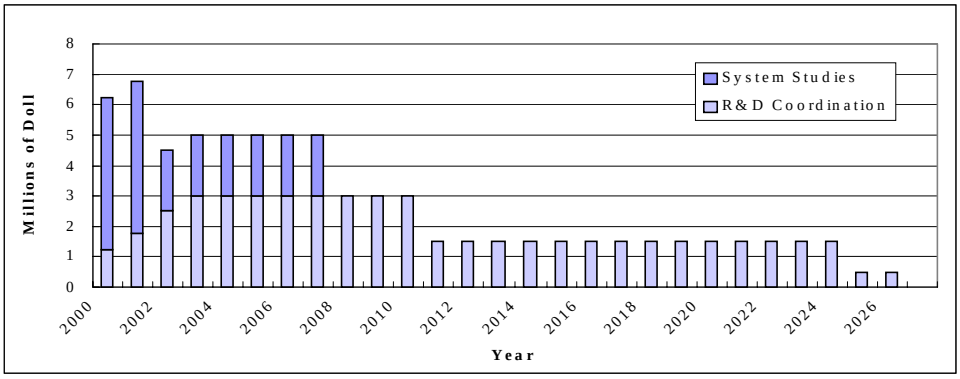


Figure 4.4. Total R&D Coordination Cost by Year

The total costs for the R&D phase of the program are summarized in Table 4.6 by program element. The time distribution of these costs over the R&D phase of the program is illustrated in Figure 4.5, also by program element.

Table 4.6. Total R&D Program Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Target/Blanket	387	226	416	1030
Accelerator	114	28	23	165
Separations	189	80	229	498
R&D Coordination	33	13	28	74
Total	723	348	696	1767

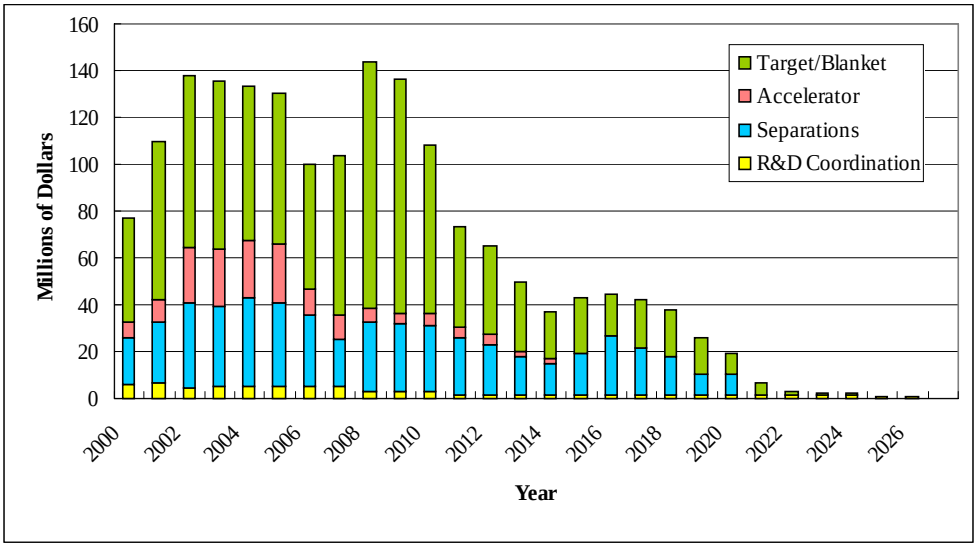


Figure 4.5. Total R&D Program Costs by Year

4.2 Demonstration Facility Costs

Estimates of the costs and durations of demonstration activities and facilities needed to move from the R&D and pilot-scale activities to the deployed ATW system were developed in the individual TWG reports for the rapid-deployment scenario and are summarized briefly here for integration with the estimated deployment costs. A full-sized accelerator would be constructed to serve the initial sub-critical reactor (transmuter), which would also be constructed full-size but initially fueled for low-power operation (~30 MWt). The transmuter would subsequently have its core size increased in steps to reach power levels of 420 MWt and 840 MWt. A turbine-generator system would be constructed to serve the first transmuter when it reaches the 420-MWt power level. A second full-sized transmuter would be

constructed, which, when connected with the turbine generator, the first transmuter, and the first accelerator, would form the first power block on the first station.

The total Target/Blanket (transmuter) demonstration costs are summarized in Table 4.7 by cost element. The time distribution of these costs over the demonstration phase of the program is illustrated in Figure 4.6, also by cost element.

Table 4.7. Total Target/Blanket (Transmuter) Demonstration Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Engineering	0	56	132	187
Construction	0	0	1664	1664
Operations	0	0	285	285
Total	0	56	2080	2136

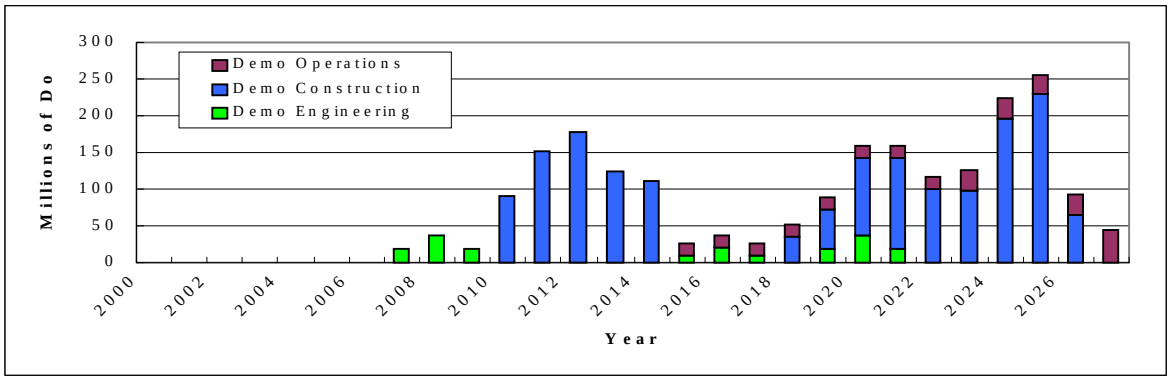


Figure 4.6. Total Target/Blanket (Transmuter) Demonstration Costs by Year

The total Accelerator demonstration costs are summarized in Table 4.8 by cost element. The time distribution of these costs over the demonstration phase of the program is illustrated in Figure 4.7, also by cost element.

Table 4.8. Total Accelerator Demonstration Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Engineering	42	383	0	425
Construction	0	0	1311	1311
Operations	0	0	744	744
Total	42	383	2055	2480

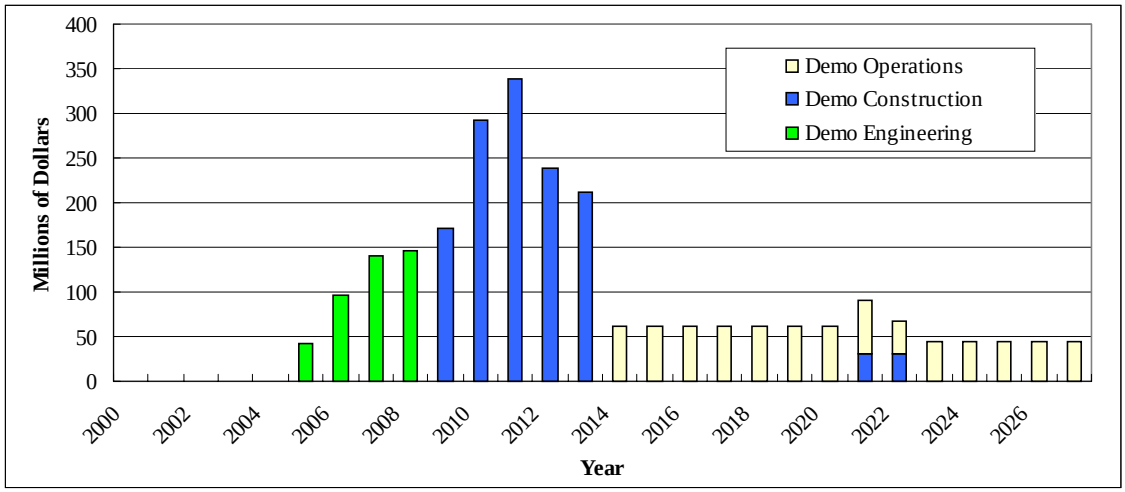


Figure 4.7. Total Accelerator Demonstration Costs by Year

The total Separations demonstration costs are summarized in Table 4.9 by cost element. The time distribution of these costs over the demonstration phase of the program is illustrated in Figure 4.8, also by cost element. The engineering costs are estimated to be 10% of the total capital costs.

Table 4.9. Total Separations Demonstration Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Engineering	3	31	104	138
Construction	0	0	1241	1241
Operations	0	0	827	827
Retrieve/Transport/Dispose	0	0	83	83
Total	3	31	2255	2289

The total demonstration integration costs are summarized in Table 4.10 by cost element. The time distribution of these costs over the demonstration phase of the program is illustrated in Figure 4.9, also by cost element.

The total costs for the demonstration phase of the program are summarized in Table 4.11 by program element. The time distribution of these costs over the demonstration phase of the program is illustrated in Figure 4.10, also by program element.

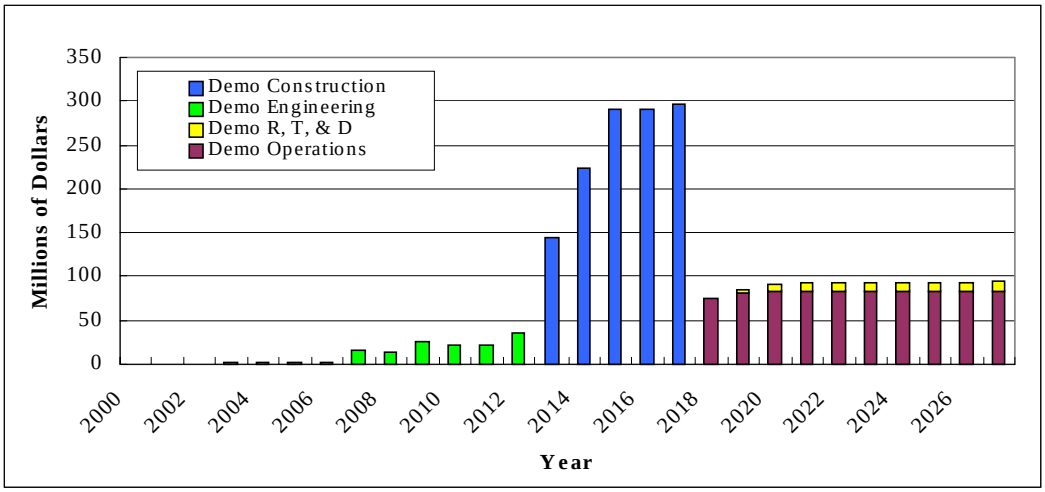


Figure 4.8. Total Separations Demonstration Costs by Year

Table 4.10. Total Demonstration Integration Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Project Support	45	33	191	269
Engineering Mgmt & Support	96	74	400	570
Project Management	7	4	24	35
Total	148	111	615	874

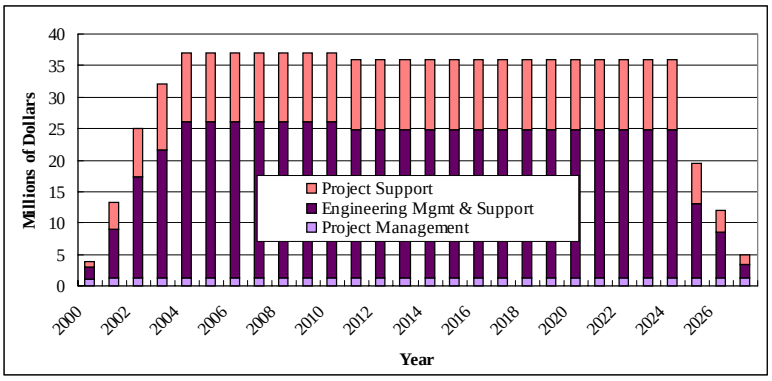


Figure 4.9. Total Demonstration Integration Costs by Year

Table 4.11. Total ATW Demonstration Costs
(millions of 1999 dollars)

Time Periods	2000-2005	2006-2008	2009-2027	Total
Target/Blanket (Transmuter)	0	56	2080	2136
Accelerator	42	383	2055	2480
Separations	3	31	2255	2289
Fuel Fabrication	0	0	620	620
Integration	148	111	615	874
Site Support	4	29	948	981
Total	198	609	8573	9380

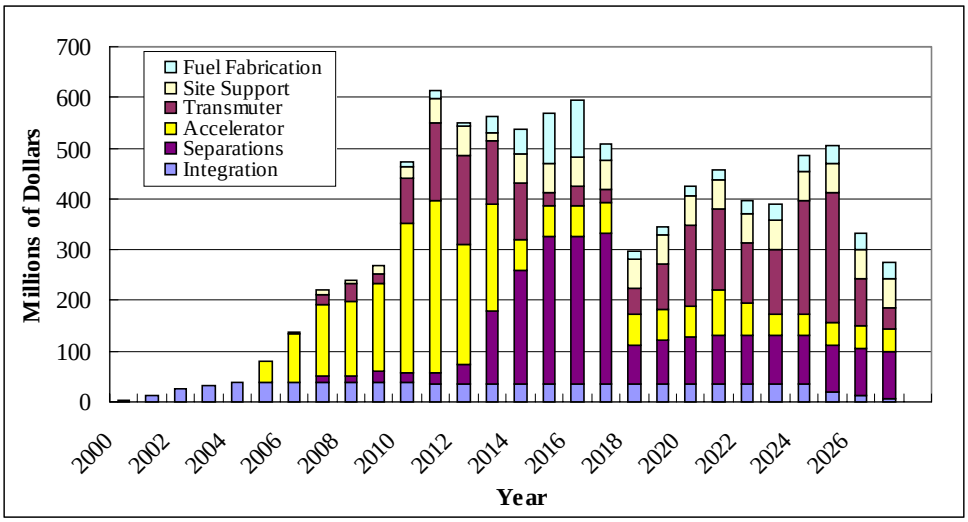


Figure 4.10. Total Demonstration Costs by Year

4.3 Full-Scale Deployed System Life-Cycle Costs

The estimated implementation costs (design, construction, operating and maintenance, and decommissioning) for the various cost elements in the full-scale deployed ATW system are developed and presented in this section. These costs include only the post-demonstration activities and do not include any construction or operations costs during the demonstration period. All costs are presented in undiscounted January 1999 dollars.

The ATW stations are postulated to be on “green field” sites, i.e., sites with no existing site infrastructure facilities in place. Therefore, it would be necessary for the appropriate site-support functions to be constructed, staffed, and placed into service by the time the first of the ATW system components is ready to begin operations. These site-support functions would be composed of such basic services as potable water and service-water systems, sanitary water and wastewater collection and

treatment systems, site electrical distribution systems, roads and sidewalks, administration buildings, station security structures such as fencing and electronic surveillance, nuclear material safeguards systems, fire protection, and emergency response and first-aid facilities, etc.

The site-support facilities in this report do not include such items as the turbine generators and their heat rejection systems, or the main electrical switchyard for delivering future generated electricity to the local power grid. These items are included in the power block equipment, to facilitate creating a unit cost structure for power blocks that is independent of the other facilities on the site. The site-support costs may appear to be underestimated because these costs are derived from the balance of plant costs for the advanced liquid metal reactor (ALMR) power blocks (GE 1995a) and from the balance of plant costs for the accelerator. However, the estimates for the other facilities on the site include some costs for support services. Thus, while not explicitly defined in all cases, it is believed that the total costs for site-support functions are reasonably well represented in the total system costs.

Because it is used as the site of the major demonstration activities (e.g., accelerator, transmuter, LWR and ATW processing, and ATW fuel fabrication), the startup schedules for facilities on Station 1 are somewhat different from the startup schedules for the subsequent stations. The site-support functions and the low-power accelerator would be the first to be placed into service (2014), followed 1 year later (2015) by the first transmuter. The fuel cycle facilities would come on-line 3 years later (2018) to produce fuel feed material and fresh ATW fuel assemblies, to process the irradiated ATW fuel, and to manufacture recycled ATW fuel assemblies for the transmuter demonstration. The first turbine-generator system would come on-line in 2023 together with the upgraded first accelerator, generating electric power to supply the station needs and for eventual external sales. The second transmuter would come on-line in 2027, joining with the first transmuter and the first turbine-generator system to form the first power block on the site. Completion of 1 year's successful full-power operation of this first power block completes the demonstration phase of the program and provides operational data needed to receive an NRC Standard Plant Certification. Subsequent power blocks on Stations 1 through 8 will be constructed and operated by private industry.

The simplified schedules for design, construction, and initial operation of the Station 1 facilities are illustrated in Figure 4.11, showing the end of the demonstration phase and the start of the privatized production phase. A similar schedule for these activities at Station 2 is also shown in Figure 4.11 for comparison. Additional schedule details are given in Appendix D.

4.3.1 Methodology

The estimates of costs for R&D and pilot activities were developed by scientists knowledgeable in the technical areas where new or additional knowledge would be needed before design and construction of demonstration plants or full-scale production stations could begin. Reasonable schedules and estimated costs for completing these investigations were developed. Similarly, estimated schedules and costs for building and operating demonstration plants for the various functions of the ATW system were developed. Details of these developments are given in the Accelerator, Separations, and Target/Blanket TWG reports (LANL 1999a, ANL 1999b, LANL 1999b).

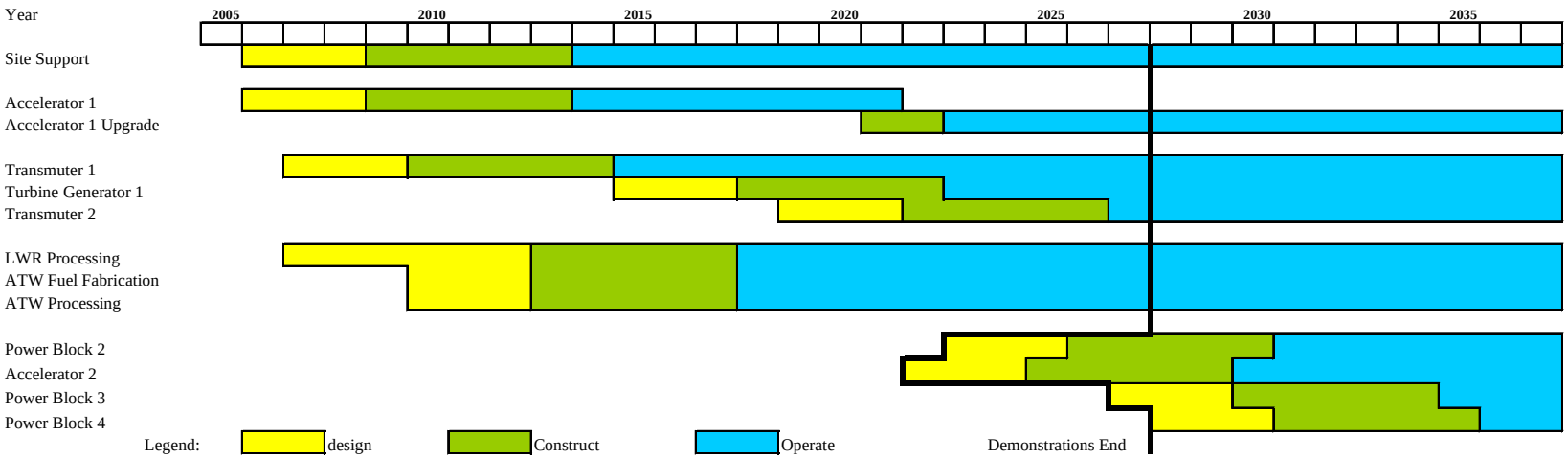
The estimated schedules and costs for deploying the full-scale ATW system were also developed, as were the estimated credits arising from the sale of the electricity generated by the system over its postulated lifetime. The estimated costs of the various facilities to be constructed and their estimated operating costs were based, where possible, on existing design studies for facilities whose functions were the same or very similar to the functions required in the proposed ATW system. Additions or deletions of functions from the existing designs were made as appropriate to satisfy the ATW mission, with associated adjustments to the estimated facility costs. Because the capacities of the original facility designs were sometimes different than the capacities needed for the ATW system, the adjusted original costs were scaled using the ratio of capacities raised to the 0.6 power. (See Appendix C for more details on scaling.)

Because some of the existing studies were performed earlier, it was sometimes necessary to escalate the adjusted facility design, construction, and operating and maintenance (O&M) costs to January 1999 dollars using DOE historical escalation data for nuclear and energy research facilities (see Appendix A). In addition, because the postulated deployed system contains many units of each type of facility (16 accelerators, 32 power blocks, 8 LWR processing/ATW fuel processing/ATW fuel fabrication and recycle plants), it was assumed that significant cost savings could be achieved due to learning experiences on the initial units. For the power blocks, the first and second transmuter units on the first station were assumed to be the first of a kind (FOAK). Power Block 2 of Station 1 was also assumed to be the first of a kind. Power Blocks 3 and 4 of Station 1 and all subsequent power blocks are assumed to be Nth of a kind (NOAK). The design and construction costs for Power Blocks 3, and 4 and all subsequent power blocks were reduced using 95% learning curve factors, as suggested in ORNL/TM-1007/R3, *Cost Estimate Guidelines for Advanced Nuclear Power Technologies* (ORNL 1993). (See Appendix B for more details on learning curve factors.) Other system unit costs (except for the accelerators) were simply reduced from the initial unit cost using 95% learning curve factors. The accelerator units costs were reduced using 85% learning curve factors for construction costs.

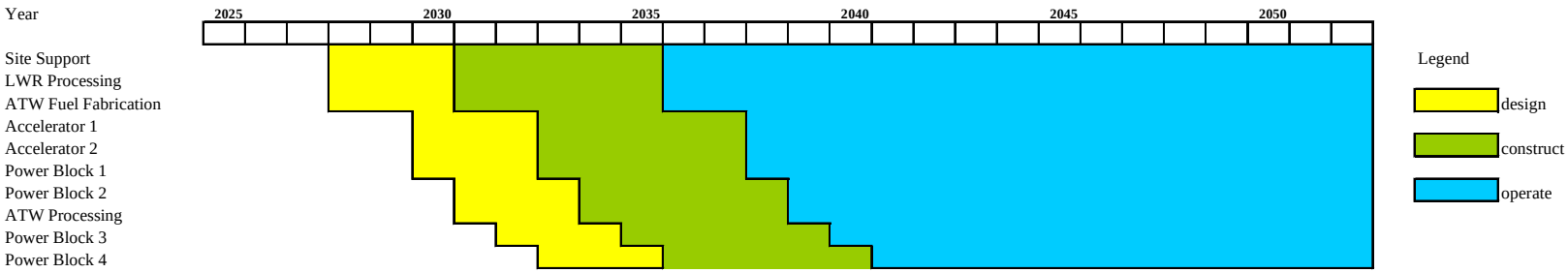
Design costs of the first units on the first ATW station were reduced by using learning curve factors to estimate the costs for subsequent units on that station and for subsequent stations. Design costs for subsequent units on the second and on subsequent stations were reduced a 0.15 factor (85%) for those units because it was assumed that the principal design work on subsequent units would be site related, not due to process changes. Those later site-related design costs were also further reduced using 95% learning curve factors.

The O&M costs for the second and subsequent units were not reduced using learning curves because the potential for any significant O&M cost reductions from learning was assumed to be small. As a result, total system operating costs may be overestimated. The O&M costs at the LWR and ATW fuel fabrication and recycle facilities were postulated to be proportional to the number of LWR SNF assemblies processed, the number of new ATW fuel assemblies fabricated, and the number of ATW assemblies processed each year, respectively.

The decommissioning costs for each radioactive unit on an ATW station were postulated to be 10% of the unreduced unit construction costs, in the same year's dollars, based on previous studies of LWR power station decommissioning (NRC 1978). Similarly, the decommissioning costs for nonradioactive



Station 1 Deployment Schedule



Station 2 Deployment Schedule

Figure 4.11. Simplified Schedules for Design, Construction and Initial Operation of Stations 1 and 2

units at an ATW station were postulated to be 5% of the unreduced unit construction costs, in the same year's dollars. These estimated decommissioning costs were also reduced using 95% learning curve factors for the second and subsequent units decommissioned.

The estimated cost for system components presented in the following subsections are "base costs," i.e., costs for the initial units of a given component prior to application of any of the learning curve and other reduction factors that were applied to subsequent units of that component in the system to adjust for mature designs and learning experiences during construction and decommissioning. These initial values were entered into a spreadsheet that modeled the demonstration, deployment, and production phases of the system's lifetime. The effects of applying these adjustment factors on the cumulative costs for design, construction, and decommissioning are illustrated in Tables 4.19 through 4.24 of Section 4.4.

In addition, estimates were developed for the costs of retrieval and transport of SNF and for transport and disposal of repository-destined wastes generated during the LWR and ATW system processes, based on information developed for DOE/RW-0510, *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program* (DOE 1998b), and for DOE/RW 0508, *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998c). For wastes destined for LLW disposal, costs were derived from NUREG-1307, Revision 8, *Report on Waste Burial Charges* (NRC 1998).

4.3.2 Accelerator Base Costs

The initial accelerator would be built at the site of the first ATW station and operate at a beam current of about 12 mA for about 7 years in the RD&D activities to improve on-line reliability of the accelerator and provide protons to drive the initial configurations of the first transmuter (at power levels ranging from 30 MWt to 420 MWt). The accelerator would then be upgraded to operate with a beam current of about 45 mA, which would be sufficient to drive two power blocks (four transmuters) at full power (840 MWt each). The installation of the first turbine-generator system would be completed at the same time as the accelerator upgrade, thus allowing the first transmuter to operate at full power, which in turn provides steam to drive the turbine-generator system to produce about 310 MWe. The electricity generated by this first combination would provide the power for the accelerator and for the rest of the station, avoiding the need to purchase large blocks of power from off-site distribution grids. The second accelerator on the site would be brought on-line in time to provide backup for the first and second power blocks and to drive the third and fourth power blocks on the station. It is anticipated that the second accelerator would incorporate the lessons learned from building and operating the first unit and would become the model for subsequent accelerator units on subsequent stations.

An important feature of the ATW accelerator system is the ability to split each of the accelerator proton beams into four separate beams and to deliver those beams to drive four separate transmuters simultaneously. Another important feature is the redundancy of beam supply provided by having the two accelerators on the site. It is postulated that one transmuter in each power block would be driven by one accelerator, and the other transmuter in each power block would be driven by the other accelerator. In this way, if one accelerator were to go out of service, one-half of each power block would continue to generate electricity to power the station and provide electricity to the external power distribution grid.

The estimated cost of the accelerators to be used to drive the transmuters was derived from the cost estimates developed for the Accelerator Production of Tritium (APT) program (TPO-P00-G-TS-00014, Rev O, *Modular Design Study, Phases I & II*, March 1999). Those estimates were developed over a period of 10 years and involved significant efforts by several commercial industrial firms. Those estimates underwent several independent cost reviews and provide a well-founded basis for estimating the cost for the ATW accelerators. The detailed development of the ATW accelerator cost estimate from the APT cost estimate is discussed in Appendix E, and the resulting base cost estimates for the ATW accelerator are summarized in Table 4.12.

Operating costs for the first accelerator unit were estimated to be $61 million per year initially, reflecting the low-power character of the unit and the RD&D initial activities. Following the accelerator upgrade and the start of electricity production at the first transmuter, the station would be supplied from the first turbine-generator unit at the site, and the costs of the electricity needed to supply the accelerator are not included in the operating costs. Similarly, the cost of electricity to supply the accelerators at subsequent stations is also not included in their operating costs. However, that electric load is subtracted from the electricity generated at the station, reducing the amount of electricity available for sale from the station. Operating costs for the second accelerator on the first station, and for subsequent stations, are estimated to be $44 million per year for each unit, reflecting the removed electricity costs and reduced staffing needed for a mature technology. These later operating costs are assumed to be essentially constant over time and are not reduced by any learning curve factors.

The cost of decommissioning the nonradioactive accelerator systems is postulated to be about 5% of the unreduced construction cost of the unit, in the same year's dollars, and is subject to the 95% learning curve factor.

4.3.3 Transmuters (Sub-Critical Reactors)

The estimated costs for design, construction, and operation for the ATW transmuters are based on information presented in the study, *ALMR Actinide Recycle System: 1994 Capital and Busbar Cost Estimates*, GEFR-00940 (GE 1995a). Cost estimates were developed in January 1994 dollars for FOAK and NOAK ALMR stations. The ALMR reactor (PRISM concept) was a sodium-cooled fast reactor fueled with metallic fuel and sized to produce 840 MWt. The ATW transmuter for this study was postulated to be essentially the same physical size and to produce the same amount of energy, thereby

Table 4.12. Estimated Base Costs for Elements of the Accelerator System (millions of 1999 dollars)

Cost Element	First Accelerator	Second Accelerator	3rd and Subsequent Units
Design	425	164	164
Construction	1251	1079	1079
Upgrade	60	--	--
O&M	61 @12 mA	44 @45 mA	44 @ 45 mA
D&D	63	54	54

permitting much of the cost information developed for the ALMR reactors to be used almost directly in estimating the costs for an ATW transmuter. Some additional costs and complexity are introduced into the ATW transmuter due to the addition of the beam tube that delivers the high-energy protons from the accelerator, the spallation target that produces the fast neutrons needed to drive the sub-critical fuel core in the transmuter, and the additional systems and circuitry associated with the combination of the transmuter with the accelerator. These additional construction costs were estimated to be $67.9 million and $56.6 million, respectively, for the first two transmuters. The additional construction cost to the second and subsequent power blocks was estimated to be $76.6 million. While the ALMR concept/ATW transmuter uses a liquid metal coolant, modifying the system to accommodate either sodium or a liquid lead-bismuth eutectic coolant should not be a major cost item and should be covered by the increases discussed above.

The estimated costs for the initial individual transmuters, turbine-generators, and associated site support functions built and used in the demonstration program and subsequently in station production, and for the individual power blocks added to complete Station 1 and the subsequent stations are summarized in Table 4.13. The derivation of these values from the original source documentation (GE 1995a) is presented in Appendix F, together with estimates of the costs for the additional components (beam tubes, spallation target assemblies, etc.) necessary to adapt the ALMR concept for ATW service. Those additional costs are incorporated into the values shown in Table 4.13.

These base values were entered into a spreadsheet that modeled the demonstration and deployment phases of the system life cycle for all stations of the system. The time-phasing of the design, construction, and initial operation of the various station elements, as modeled in the spreadsheet, is illustrated for Stations 1 and 2 in Figure 4.11.

The estimated site-support costs derived from the ALMR data represent the basic site infrastructure costs for an ATW site, including such things as streets and sidewalks, administration buildings, process and potable water systems, fire protection and emergency first aid services, site electrical distribution system, etc. Each station's site support is sized to support operations at four power blocks and associated accelerators and fuel processing and fabrication facilities. These functions are common to every station constructed throughout the program, and are quite straightforward to design and construct. Thus, the site-support cost for the first station is FOAK, for the second and subsequent stations the site-support costs are NOAK with the base costs for the site support functions for subsequent stations reduced using the 0.15

Table 4.13. Estimated Base Design, Construction, D&D, and Operating Costs for Transmuters (millions of 1999 dollars)

Cost Element	1st and 2nd Transmuters (FOAK)	1st Turbine-Generator (FOAK)	1st Station Site Support (FOAK)	1st Power Block (FOAK)	1st Power Block (NOAK)	Station Site Support (NOAK)
Design	74.0	39.2	17.5	144.8	123.8	16.3
Construction	655.7	352.5	157.5	1304.0	1114.6	147.0
D&D	65.6	35.3	7.9	130.4	111.4	7.4
O & M	16.7/y	10.2/y	57.6/y	25.1/y		57.6/y

factor for design and the 95% learning curve factors for design and construction. Those costs for support services peculiar to a given ATW function (e.g., accelerators, fuel processing), are incorporated into the capital cost estimates for those functions.

4.3.4 Separations and Recycle Facilities

There are two types of fuel processing functions in the ATW system: 1) an LWR processing function that processes the SNF assemblies into a transuranic (TRU) stream for ATW fuel, a uranium stream for storage or disposal, a fission product stream for treatment and disposal, and an irradiated metals waste stream for disposal; and 2) an ATW recycle processing function that processes irradiated ATW fuel into a TRU stream for recycling into additional ATW fuel, an irradiated metals waste stream for disposal, and a fission product stream for treatment and disposal. Selected fission products are extracted in both processes for target fabrication. Both processing functions are combined into a single structure together with the ATW fuel fabrication function at the ATW site, to facilitate internal movement of radioactive materials among the fuel processing functions. The estimated costs for these facilities are presented in the subsequent subsections.

4.3.4.1 LWR Processing

The estimated costs for design, construction, and operation for the LWR processing function are based on information presented in the TWG Separations report (ANL 1999b). Each production station is postulated to contain an LWR processing function to separate the fission products and transuranics from the residual uranium, and to prepare the transuranics and technetium and iodine for fabrication into ATW fuel assemblies and target assemblies. The base cost data were developed for the initial LWR processing facility used in the demonstration activities and subsequent production activities at Station 1. The facility was postulated to process 210 MTU-SNF per year and produce 2.19 MT per year of TRU for ATW fuel, 28.2 m^3 of class C uranium oxide for disposal, 7.24 m^3 of metallic waste, and 42.9 m^3 of fission product wastes in a ceramic matrix.

Other ATW stations were postulated to have different processing rates, as needed, to provide sufficient TRU feed material to the ATW fuel fabrication facilities to fuel the power blocks as they came on-line. The processing rates for the various stations are given in Table 4.14. The costs shown are base costs for the stated capacities, without learning curve adjustments, but include a 25% contingency on both design and construction costs.

Table 4.14. Estimated Capacity and Base Costs for LWR Processing (millions of 1999 dollars)

Station Number	Capacity (MTU-SNF/yr)	Design	Construction	D&D	O&M Costs per year
1	210	73.7	663.6	66.4	56.25
2, 3	685 each	149.9	1348.9	134.9	114.3
4, 5, 6, 7, 8	175 each	66.1	594.8	59.5	50.4

The design and constructions costs shown in Table 4.14 are distributed over periods of 6 and 5 years, respectively, for the first station, reflecting the initial demonstration status of the facility. In subsequent stations, the design and construction costs are distributed over periods of 3 and 5 years, with percents expended per year of 25%, 50%, 25% for design, and 10%, 15%, 30%, 35%, 10%, for construction.

The O&M costs for the LWR processing function are postulated to be proportional to the facility throughput in MTU-SNF, using a 0.6 power scaling factor. Thus, the O&M costs in any given year (X) are given by:

$$O\&M(X) = O\&M\ (1)\ (X\ MTU/210\ MTU)^{0.6} \text{ or } \$56.3\ M\$/yr \times (X\ MTU/210\ MTU)^{0.6}.$$

The LWR processing function at each ATW production station is postulated to begin processing spent LWR fuel several years in advance of the startup of any of the transmuters to provide the needed transuranic feed material to the additional feed material needed during the approach to equilibrium conditions in the transuranic recycle scheme. Feed material for the initial core loading and for the initial fuel reload at the first transmuter on Station 1 would be provided from the processing and fabrication pilot and demonstration activities supporting that station. Surplus production at the first station would provide the feed material for the first cores and first reloads at the second station. The Stations 2 and 3 LWR processing functions would be sized to produce the feed material needed for the initial cores and first reloads at subsequent stations in the system, allowing the LWR functions at those latter stations to be sized to provide only the continuing feed material for their own sites. The processing capacities (in MTU-SNF per year) postulated for the various stations are shown in Table 4.14. The LWR processing functions at the production stations will continue through the year 2073, when all of the forecast civilian spent fuel inventory (86,317 MTU) will have been processed. The surplus feed material produced at Stations 1, 2, and 3 will be stockpiled at those stations until needed at the other stations.

An interesting figure of merit for the LWR processing facilities at the various ATW stations is given in Table 4.15, where the cost per kilogram of material processed is developed for each station. This figure of merit is calculated by dividing the life-cycle cost of the facility by the amount of product processed during that lifetime.

Table 4.15. Figures of Merit for LWR Processing Facilities

Station No.	Years of Operation	MTU-SNF Processed	Life-Cycle Cost (millions)	Figure of Merit ($/kg Processed)
1	56	11,358	3,931	346
2	38	25,402	10,306	406
3	36	24,032	9,663	402
4	34	5,790	2,118	366
5	32	5,440	2,018	371
6	30	5,090	1,920	377
7	28	4,740	1,823	385
8	26	4,467	1,772	397

4.3.4.2 ATW Processing and Recycle

Each production station is postulated to contain an ATW spent fuel processing function to separate the transuranics removed from the ATW spent fuel and to mix the recycled transuranics with new transuranic feed material from the LWR processing function for use in new ATW fuel assemblies, and to recycle technetium and iodine from the ATW spent fuel into target assemblies. The estimated base costs for design, construction, and operation for the ATW spent fuel processing and recycle function are based on information developed by the TWG Separations report (ANL 1999b) and are displayed in Table 4.16. A 25% contingency is included in the design and construction cost estimates.

The base design and construction costs shown in Table 4.16 are distributed over periods of 3 and 5 years, respectively, for all stations, with percents expended per year of 25%, 50%, 25% for design, and 10%, 15%, 30%, 35%, 10%, for construction. The initially low production rate at Station 1 resulted in a larger figure of merit than the remaining stations. Because of the reduced capital costs and the constant number of years of operation (63) and the constant amount of product processed for the ATW processing facilities, the figures of merit for subsequent facilities decrease slowly from Station 2 to Station 8.

The ATW spent fuel processing and recycle function at each ATW production station is postulated to begin processing irradiated ATW fuel assemblies several years following startup of the first transmuter at that site, to provide the recycle transuranics needed for subsequent transmuter core loadings. The ATW spent fuel processing and recycle functions at each production station will continue until about 2 years following shutdown of the last power block on that station.

4.3.5 ATW Fuel Fabrication

The estimated costs for design, construction, and operation for the ATW fuel fabrication function are based on information presented in the TWG Separations report (ANL 1999b) and on estimates of O&M costs for the ALMR fuel processing and fabrication plant (GE 1995b). Each production station is postulated to contain an ATW fuel fabrication function to fabricate the transuranics removed from the LWR and ATW spent fuel into new ATW fuel assemblies and to fabricate technetium and iodine into target assemblies.

The data used to develop the cost estimates for ATW fuel fabrication are displayed in Table 4.17, together with the calculated figure of merit for the facility. The design and construction estimates include a 25% contingency. The first row in the table represents the estimates developed for a 1056-assemblies-per-year facility, from the TWG Separations report and ALMR study data. The second row is the result

Table 4.16. Capacity, Estimated Base Costs, and Figures of Merit for ATW Spent Fuel Processing and Recycle Functions

Station No.	Capacity (MT-TRU/yr), (MT-TRU/life)	Design (millions)	Construction (millions)	D&D (millions)	O&M Costs (millions/yr)	Life-Cycle Cost (millions)	10^3 $/kg Processed
1	6.514, (404.5)	64.2	577.5	57.8	27.6	2,918	7.21
8	6.514, (395.4)	8.3	495	49.5	27.6	2,302	5.82

Table 4.17. Estimated Capacity, Base Costs, and Figures of Merit for ATW Fuel Fabrication

Capacity (assemblies/yr) (@15.72 kg-TRU/assm.)	Design (millions)	Construction (millions)	D&D (millions)	Lifetime Processing (kg-TRU)	O&M Costs (millions/yr)	Life-Cycle Cost (millions)	10^3 $/kg Processed
1056	55.0	495.0	49.5		145.2		
528 (Station 1)	36.3	326.6	32.7	532,520	80.7	5,994	11.3
528 (Station 8)	4.2	280.0	28.0	514,610	80.7	1,379	2.7

of scaling the first row to a nominal annual capacity of 528 assemblies per year, which is the assumed capacity for all of the ATW fuel fabrication facilities, and using the life-cycle costs for the first ATW station. The third row is the result for the eighth station of the system. The Station 1 fabrication facility is assumed to operate at rather low levels of capacity during the demonstration phase, with equilibrium production over the rest of the station lifetime. Each of the other station fabrication facilities is assumed to operate at essentially full capacity for 63 years. The long operating life of the Station 1 facility, coupled with its less than full capacity production during its early years, resulted in the much larger figure of merit compared with the Station 8 facility.

The design and construction costs are rough order-of-magnitude estimates based on limited information on fuel fabrication plants around the world and could easily be larger or smaller. The O&M costs are developed from data (GE 1995b) for the ALMR fuel fabrication facilities. The O&M costs are a strong function of the number of assemblies produced each year, because of the cost of cladding and other assembly structural components, and are separated into a fixed and a variable portion. The fixed cost portion is composed of the basic staffing costs for the facility, which are essentially independent of the annual throughput, and the basic consumables needed to support the facility. The variable cost portion includes the staff directly engaged in production operations and the consumables (cladding and internal hardware) associated with the production of the new fuel assemblies, and is postulated to be proportional to the number of fuel assemblies produced each year.

In the initial years of production, the annual production rates will be significantly lower than at the equilibrium production of 528 assemblies per year postulated for the facilities in the ATW system. The algorithm for computing these annual costs is

$$\text{Annual O\&M cost} = 16.162 + 70.393 \times (\text{Number of assemblies}/576)$$

where 576 is the number of assemblies produced by the reference ALMR fuel fabrication facility.

The design and construction costs shown in the table are distributed over periods of 3 and 5 years, respectively, for the first and subsequent stations, with percents expended per year of 25%, 50%, 25% for design, and 10%, 15%, 30%, 35%, 10%, for construction.

The ATW fuel fabrication function at each ATW production station is postulated to begin fabricating ATW fuel assemblies several years in advance of startup of any of the transmuters, to provide the fuel

assemblies needed for the initial transmuter core loadings. The ATW fuel fabrication functions at each of the production stations will continue until about one year before shutdown of the last power block on each station.

4.3.6 Site Support

The site-support function for the ATW station primarily comprises those portions of the power block balance of plant not related to the turbine-generator system (i.e., potable water and service water systems, sanitary water and wastewater collection and treatment systems, site electrical distribution systems, roads and sidewalks, administration buildings, station security structures such as fencing and electronic surveillance, nuclear material safeguards systems, fire protection, emergency response and first-aid facilities, etc). The costs of those support facilities that are peculiar to a given station function (e.g., accelerators, fuel processing) are included in the costs of those facilities.

The costs for the site-support function at a station are derived from the ALMR reactor station data (GE 1995a), as illustrated in Appendix F. The turbine-generator cost elements were subtracted from the balance of plant costs for a power block, i.e., the balance of plant costs were separated into the costs for the turbine-generator system and the costs for the assorted site-support functions. The results of this analysis to obtain estimates for single transmuters, single turbine generators, and site-support functions for a four-power block station are given in Section 4.3, Table 4.13. The net site-support function costs, thus separated, are given in Table 4.18.

Table 4.18. Estimated Base Costs for Site-Support Functions
(millions of 1999 dollars)

Station	Design	Construction	D&D	O&M
1	17.5	157.5	15.6	57.6/y
2 – 8	16.3	147.3	14.7	57.6/y

The design costs for Station 1 reflect the complications of that station being the first station built and the site for the demonstration activities. The base site-support design and construction costs for the second and subsequent stations were reduced about 7%, reflecting the mature nature of the design and the standardization of the structures and materials in the support functions. The values in the table are the base costs, not reduced by learning curve adjustments for being the Nth unit designed and constructed.

4.3.7 Retrieval, Transport, and Disposal

The following estimated costs are developed in this subsection:

- retrieving and transporting SNF to the LWR processing function
- transporting and disposing of the recovered uranium in a LLW disposal facility

- transporting the separated and treated fission products and the irradiated fuel assembly hardware back to the repository where it is re-emplaced

- transporting the treated and packaged residual fission products from the ATW station to the repository where they are emplaced

- transporting the irradiated ATW fuel assembly hardware to a LLW disposal facility where it is disposed.

The basic approach is to relate each of these costs to the quantity of SNF handled in the system. The total quantity of SNF postulated to be treated within the ATW system (86,317 MTU, as given in DOE/RW-0510 [DOE 1998b]) is retrieved and transported to the LWR facility. From Table 11 of that reference and as subsequently clarified[(a)] the cost of retrieval of SNF from the repository are calculated from:

$$\frac{0.736\,\mathrm{x}\,[\$4{,}320\,\mathrm{M(Surface)} + \$340\,\mathrm{M\,(subsurface)} + \$990\,\mathrm{M\,(RIMS)}]}{86{,}317\,\mathrm{MTU} - \mathrm{SNF}} = 0.04818\,\mathrm{M\$\,/\,MTU}$$

where 0.736 is the civilian share factor for repository volume. A subsequent review by Office of Civilian Radioactive Waste Management staff[(b)] concluded that for the conditions postulated for ATW (i.e., waste packages shipped to the ATW station intact) the retrieval costs would be only incremental to the costs at the already operating repository, and that incremental cost would be about 0.01 M$/MTU.

The same review concluded that the transportation costs for moving the SNF package from the repository to the ATW station would also be an incremental cost of about 0.02 M$/MTU to an already operating transport system. Similarly, the review concluded that the emplacement costs for waste packages containing ATW high-level wastes would be about 0.01 M$/MTU, again an incremental cost in an already operating system. This latter cost assumed that the wastes were containerized appropriately and loaded into excess emplacement packages available at the ATW station from unloading incoming LWR SNF.

Considering that the initial SNF inventory has been postulated to occupy about 7642 waste packages (DOE 1998c), the incremental cost per package of LWR-SNF to be emplaced is given by

$$(0.01 + 0.02)\ \mathrm{M\$/MTU} \times 86{,}317\ \mathrm{MTU}/7642\ \mathrm{packages} = 0.3389\ \mathrm{M\$/waste\ package}$$

This same value is then used to estimate the incremental cost for transport and emplacement of ATW waste packages at the repository. Each waste package is postulated to contain 7.34 cubic meters of waste, which may be LWR fission products, ATW fission products, or LWR and ATW metal wastes arising from removed fuel cladding and assembly hardware.

(a) Private Communication: E-mail from Les.Meyer@rw.doe.gov to ri_smith@owt.com, dated 5/28/99.
(b) Private Communication: E-mail from Dale.Lancaster@rw.doe.gov to ri_smith@pnl.gov, dated 6/30/99.

The slightly enriched uranium recovered from the SNF at the LWR processing function is treated and packaged for disposal at a regulated LLW disposal facility. It is postulated that 95.8% of the heavy metal in the SNF is uranium. From NUREG-1307, Revision 8 (NRC 1998), the cost for disposal of radioactive metals at a LLW disposal facility ranges from $0.87 to $3.00 per pound of metal. Assuming the larger value applies, the cost for disposal of the recovered uranium is 0.0066 M$/MTU, or when escalated to 1999 dollars, 0.00673 M$/MTU-SNF. The transport cost of shipping the packaged uranium by truck as LLW would be about $5000 per shipment of about 16 metric tons of uranium, or less than $400 per metric ton (0.0004 M$/MTU-SNF). Thus, the total transport/disposal cost for LLW uranium is estimated by:

$$(0.958) \times (0.0004 + 0.00673) \text{ M\$/MTU} = 0.00683 \text{ M\$/MTU}$$

The total cost for the retrieval, transport, and disposal activities over the life of the ATW system is given by:

$$86{,}317 \text{ MTU} \times (0.03 + 0.00683) \text{ M\$/MTU} + 0.3389 \text{ M\$/waste package}$$

The cost of these activities for the ATW program is estimated to be $4.3 billion in 1999 dollars.

4.4 Application of Adjustment Factors to Base Cost Estimates

The estimated base costs for the components of an ATW station, presented in Section 4.3, were put into the system cost model spreadsheet as the estimates for the first (and sometimes the second) unit of each component of the total system. These initial estimates were adjusted for learning experience for subsequent units by applying learning curve factors (see Appendix B). Ninety-five percent learning curve factors were applied to Nth of a kind (NOAK) units for design and construction, for all units except accelerators where an 85% learning curve factor was applied to construction of NOAK accelerators.

The effects of applying these factors internally in the System Cost Model spreadsheet are illustrated for the six station components in Tables 4.19 through 4.24 of this subsection where the reduced estimated costs for each successive unit constructed are given. The total estimated costs for design, construction, and decommissioning of each type of component in the postulated ATW system are also given in the tables, illustrating why the total system cost for a given component is <u>not</u> simply the product of the initial base cost and the number of units in the system.

4.4.1 Adjusted Accelerator Costs

The reductions to the base estimated costs for design, construction, and decommissioning for the system accelerators are shown in Table 4.19. Costs shown in this table include both demonstration and production phases of the system lifetime.

The design and construction costs for the first ATW accelerator on the first station are estimated to be $425 million and $1251 million, respectively, in 1999 dollars. The subsequent upgrade costs to increase the beam power from 12 mA to 45 mA are estimated to be an additional $60 million. The design and

Table 4.19. Effects of Adjustments to Accelerator Base Cost Estimates

	Unit	Accelerators			
		Seq. No.	Design	Construct	D&D
STATION No. 1	1	1	425.00	1251.00	63.00
	Upgrade	1	0.00	60.00	0.00
	2	1	164.00	1079.00	54.00
STATION No. 2	1	2	155.80	917.13	54.00
	2	3	22.68	833.94	41.70
STATION No. 3	1	4	22.68	779.54	38.98
	2	5	22.20	739.80	36.99
STATION No. 4	1	6	21.55	708.83	35.44
	2	7	21.30	683.67	34.18
STATION No. 5	1	8	21.09	662.59	33.13
	2	9	20.91	644.54	32.23
STATION No. 6	1	10	20.75	628.81	31.44
	2	11	20.60	614.91	30.75
STATION No. 7	1	12	20.47	602.49	30.12
	2	13	20.35	591.29	29.56
STATION No. 8	1	14	20.24	581.10	29.06
	2	15	20.13	571.78	28.59
Total, All Stations			1,019.74	11,950.45	603.17

construction costs for the second accelerator on the station are estimated to be about $164 million and $1079 million, respectively. The reduced design cost reflects the mature technology, and the reduced accelerator costs reflect the reduced cost of support functions on that site for the second unit. The base design cost for the first accelerator on the second station was also estimated to be $164 million, and the base construction cost for that unit was also estimated to be $1079 million. Design costs for subsequent units were reduced using a 95% learning curve and by a 0.15 factor to reflect a mature design, and subsequent construction costs were reduced using a 85% learning curve. The total capital cost, including demonstration costs, for all accelerators at all stations is estimated to be $13.6 billion, in 1999 dollars.

The decommissioning costs for the two units on the first station are estimated to be $117 million. Decontamination and decommissioning (D&D) costs for subsequent units are reduced using a 95% learning curve factor, and the total D&D cost for all accelerators is estimated to be about $603 million in 1999 dollars.

The total post-demonstration life-cycle costs for accelerators in the ATW system is estimated to be about $56 billion in 1999 dollars.

4.4.2 Adjusted Transmuter Costs

The reductions to the base estimated costs for design, construction, and decommissioning for the system transmuters are shown in Table 4.20. Costs shown in this table include both demonstration and production phases of the system lifetime.

Table 4.20. Effects of Adjustments to Transmuter Base Cost Estimates

		Power Blocks		
STATION No. 1	Seq. No.	Design	Construct	D&D
Turbine-Generator	1	39.20	352.50	17.63
Transmuter 1	1	74.00	655.60	65.56
Transmuter 2	1	74.00	655.60	65.56
Power Block 2	1	144.80	1304.00	130.40
Power Block 3	1	144.80	1114.60	111.46
Power Block 4	2	137.56	1058.87	105.89
STATION No. 2				
Power Block 1	3	133.49	1027.57	102.76
Power Block 2	4	19.60	1005.93	100.59
Power Block 3	5	19.28	989.45	98.95
Power Block 4	6	19.02	976.19	97.62
STATION No. 3				
Power Block 1	7	17.34	965.12	96.51
Power Block 2	8	17.17	955.63	95.56
Power Block 3	9	17.02	947.34	94.73
Power Block 4	10	16.89	939.98	94.00
STATION No. 4				
Power Block 1	11	16.77	933.37	93.34
Power Block 2	12	16.66	927.38	92.74
Power Block 3	13	16.56	921.91	92.19
Power Block 4	14	16.47	916.87	91.69
STATION No. 5				
Power Block 1	15	16.39	912.20	91.22
Power Block 2	16	16.31	907.85	90.79
Power Block 3	17	16.24	903.79	90.38
Power Block 4	18	16.17	899.97	90.00
STATION No. 6				
Power Block 1	19	16.10	896.38	89.64
Power Block 2	20	16.04	892.98	89.30
Power Block 3	21	15.98	889.76	88.98
Power Block 4	22	15.93	886.71	88.67
STATION No. 7				
Power Block 1	23	15.88	883.79	88.38
Power Block 2	24	15.83	881.02	88.10
Power Block 3	25	15.78	878.36	87.84
Power Block 4	26	15.73	875.81	87.58
STATION No. 8				
Power Block 1	27	15.69	873.37	87.34
Power Block 2	28	15.65	871.02	87.10
Power Block 3	29	15.61	868.76	86.88
Power Block 4	30	15.57	866.59	86.66
Total, all stations		1195.53	30,836.28	3,066.00

The first and second transmuters and the associated turbine-generator unit were designated as FOAK single units and form the first power block of Station 1. No adjustments were made to those costs for learning curves on design and construction. The second power block on Station 1 was designated as the FOAK unit for the system, and the third power block on Station 1 was designated as the first NOAK unit. Estimated design and construction costs for Power Block 4 on Station 1 were reduced from the Power Block 3 costs by 95% learning curve factors. On Station 2 and on subsequent stations, the power block costs were reduced from the base NOAK power block cost using 95% learning curve factors. The design costs for the second and subsequent power blocks on Station 2 and on subsequent stations were additionally reduced from the base design cost by a factor of 0.15 to reflect the maturity of the design.

Decommissioning costs for the radioactive power blocks are postulated to be about 10% of unreduced construction cost of a block in the same year's dollars. The D&D costs are reduced for successive units using 95% learning curve factors.

The total capital cost for all power blocks at all stations, including demonstration costs, is estimated to be $32 billion in 1999 dollars. The post-demonstration cost for design, construction, operation, and decommissioning of the transmuter/power generation power blocks at all eight production stations was estimated to be $82.6 billion in 1999 dollars. Decommissioning of the radioactive transmuter units are estimated to cost $3.1 billion in 1999 dollars.

4.4.3 Adjusted LWR Processing Costs

The reductions to the base estimated costs for design, construction, and decommissioning for the system LWR processing function are shown in Table 4.21. Costs shown in this table include both demonstration and production phases of the system lifetime.

The design costs for this function at subsequent stations are reduced from the initial function costs by a factor of 0.15 to reflect a more mature design and the few design changes expected to be needed. Both design and construction costs for this function at subsequent stations are additionally reduced using 95% learning curve factors.

Table 4.21. Effects of Adjustments to LWR Processing Base Cost Estimates

		LWR Processing		
	Seq. No.	Design	Construct	D&D
STATION No. 1	1	73.70	663.60	66.36
STATION No. 2	2	149.90	1281.46	134.89
STATION No. 3	3	20.72	1243.60	124.36
STATION No. 4	4	8.94	536.84	53.68
STATION No. 5	5	8.80	528.05	52.80
STATION No. 6	6	8.68	520.97	52.10
STATION No. 7	7	8.58	515.06	51.51
STATION No. 8	8	8.50	510.00	51.00
Total, all stations		287.81	5,799.58	586.70

The costs for decommissioning the radioactive LWR processing facility are postulated to be 10% of the unreduced construction cost of the facility. D&D costs at subsequent stations are reduced using 95% learning curve factors.

The total capital cost for all LWR processing functions at all stations, including demonstration costs, is estimated to be $6.1 billion in 1999 dollars. The post-demonstration cost for design, construction, operation, and decommissioning of the LWR processing functions at all eight production stations was estimated to be $32.3 billion in 1999 dollars, not including any retrieval, transport, or disposal costs.

Decommissioning of the radioactive LWR processing functions is estimated to cost $587 million in 1999 dollars.

4.4.4 Adjusted ATW Processing Costs

The reductions to the base estimated costs for design, construction, and decommissioning for the system LWR processing function are shown in Table 4.22. Costs shown in this table include both demonstration and production phases of the system lifetime.

The design costs for this function at subsequent stations are reduced from the initial function estimate by a factor of 0.15 to reflect a more mature design and the few changes expected to be needed. Both design and construction costs for this function at subsequent stations are additionally reduced using 95% learning curve factors.

The costs for decommissioning the radioactive ATW processing and recycle function are postulated to be 10% of the unreduced construction cost of the facility. D&D costs at subsequent stations are reduced using a 95% learning curve factor.

The total capital cost for all ATW processing functions at all stations, including demonstration costs, is estimated to be $4.3 billion in 1999 dollars. The post-demonstration cost for design, construction, operation, and decommissioning of the ATW processing functions at all eight production stations was estimated to be $18.3 billion in 1999 dollars, not including any retrieval, transport, or disposal costs.

Table 4.22. Effects of Adjustments to ATW Processing Base Cost Estimates

		ATW Processing		
	Seq. No.	Design	Construct	D&D
STATION No. 1	1	64.20	577.50	57.75
STATION No. 2	2	9.15	548.63	54.86
STATION No. 3	3	8.88	532.41	53.24
STATION No. 4	4	8.69	521.19	52.12
STATION No. 5	5	8.55	512.66	51.27
STATION No. 6	6	8.43	505.79	50.58
STATION No. 7	7	8.34	500.05	50.01
STATION No. 8	8	8.26	495.13	49.51
Total, all stations		124.50	4,193.36	419.34

Decommissioning of the radioactive LWR processing functions is estimated to cost $419 million in 1999 dollars.

The post-demonstration life-cycle cost for designing, constructing, operating, and decommissioning the total LWR and ATW fuel processing functions at all eight production stations is estimated to be $50.6 billion in 1999 dollars, not including any retrieval, transport, or disposal costs.

4.4.5 Adjusted ATW Fuel Fabrication Costs

The reductions to the base estimated costs for design, construction, and decommissioning for the system ATW fuel fabrication function are shown in Table 4.23. Costs shown in this table include both demonstration and production phases of the system lifetime.

The design costs for subsequent fuel fabrication functions at other stations are reduced from the initial function costs by a factor of 0.15 to reflect a more mature design and the few changes expected to be needed. Both design and construction costs for subsequent functions are additionally reduced using 95% learning curve factors.

The costs for decommissioning the radioactive fuel fabrication function are postulated to be 10% of the unreduced construction cost of the facility in the same year's dollars. D&D costs at subsequent stations are reduced using a 95% learning curve factor.

The total capital cost for all ATW fuel fabrication functions at all stations, including demonstration costs, is estimated to be $2.4 billion in 1999 dollars. The post-demonstration cost for design, construction, operation, and decommissioning of the ATW fuel fabrication functions at all eight production stations was estimated to be about $43 billion in 1999 dollars, not including any retrieval, transport, or disposal costs.

Decommissioning of the radioactive ATW fuel fabrication functions is estimated to cost $237 million in 1999 dollars.

Table 4.23. Effects of Adjustments to ATW Fuel Fabrication Base Cost Estimates

		ATW Fuel Fabrication		
	Seq. No.	Design	Construct	D&D
STATION No. 1	1	32.66	326.60	32.66
STATION No. 2	2	4.65	310.27	31.03
STATION No. 3	3	4.52	301.10	30.11
STATION No. 4	4	4.42	294.76	29.48
STATION No. 5	5	4.35	289.93	28.99
STATION No. 6	6	4.29	286.04	28.60
STATION No. 7	7	4.24	282.80	28.28
STATION No. 8	8	4.20	280.02	28.00
Total, all stations		63.33	2,371.52	237.15

4.4.6 Adjusted Site Support Costs

The reductions to the base estimated costs for design, construction, and decommissioning for the system site-support function are shown in Table 4.24. Costs shown in this table include both demonstration and production phases of the system lifetime.

The construction and decommissioning costs for the site-support functions are reduced using the 95% learning curve factor for Station 2 and all subsequent stations. The design costs for Station 3 and all subsequent stations are further reduced by a factor of 0.15 to reflect the mature technology involved and the minimal changes that might be needed for successive facilities.

The cost of decommissioning the nonradioactive site-support functions is postulated to be 5% of the unreduced capital cost of the units, in the same year's dollars, and these costs are reduced for subsequent stations using 95% learning curve factors.

The total capital cost for all ATW station site-support functions at all stations, including demonstration costs, is estimated to be $1.2 billion in 1999 dollars. The post-demonstration cost for design, construction, operation, and decommissioning of the ATW site support functions at all eight production stations was estimated to be about $31.7 billion in 1999 dollars, not including any retrieval, transport, or disposal costs.

Decommissioning of the nonradioactive ATW site-support functions is estimated to cost $55 million in 1999 dollars.

4.5 Time Distribution of Total Program Costs and Revenues

The estimated undiscounted ATW program costs, presented in previous subsections as totals over the system lifetime, by cost element, are displayed in Section 4.5.1 to show the percentage of each cost element of the total station capital cost, of station life-cycle operating cost, and total system life-cycle cost. Also shown are the annual expenditures for each cost element necessary to proceed from the year 2000 when R&D begins until the full-scale ATW system has completed its mission of transmuting the

Table 4.24. Effects of Adjustments to the Site-Support Base Cost Estimates

		Site Support		
	Seq. No.	Design	Construct	D&D
STATION No. 1	1	17.50	157.50	7.88
STATION No. 2	1	16.30	147.00	7.35
STATION No. 3	2	2.32	139.65	6.98
STATION No. 4	3	2.42	135.52	6.78
STATION No. 5	4	2.37	132.67	6.63
STATION No. 6	5	2.33	130.49	6.52
STATION No. 7	6	2.30	128.75	6.44
STATION No. 8	7	2.27	127.29	6.36
Total, all stations		47.81	1,098.87	54.94

residual transuranic elements in SNF into less hazardous materials. Along with the program costs, the credits arising from the electricity generated during the program lifetime are presented, and the net financial cost or benefit of the program is shown. In addition, the results of a net present value analysis of the costs and revenues streams are presented in Section 4.5.2.

4.5.1 Summary Displays of Undiscounted Costs and Revenue Streams

The percents of the capital cost of a typical production station (Station 4) are illustrated in Figure 4.12 by the principal cost elements. The total capital cost for that station is estimated to be $6.7 billion in undiscounted 1999 dollars, which reflects reductions for learning curve factors and other adjustments.

The percents of the operating cost of a typical production station (Station 4) are illustrated in Figure 4.13 by the principal cost elements. The total life-cycle operating cost for that station is estimated to be $36.7 billion in 1999 dollars, including retrieval, transport, and disposal activities.

The percents of the deployed system undiscounted total lifecycle costs (including RD&D activities) are illustrated in Figure 4.14, by the principal cost elements. The total life-cycle cost for the deployed system is estimated to be $279.4 billion in 1999 dollars.

The time distribution of the total undiscounted ATW program life-cycle costs is illustrated in Figure 4.15 by the principal cost elements.

Similarly, the time distribution of the total undiscounted ATW system program cost is shown in Figure 4.16 together with a possible revenue stream arising from selling the electricity produced by the system over the system life-cycle, assuming a possible sales price of 43 mills/kWh. The 43 mills/kWh production cost value is estimated by the Electric Power Research Institute (EPRI) to be the point at which nuclear power production is competitive with fossil power production.

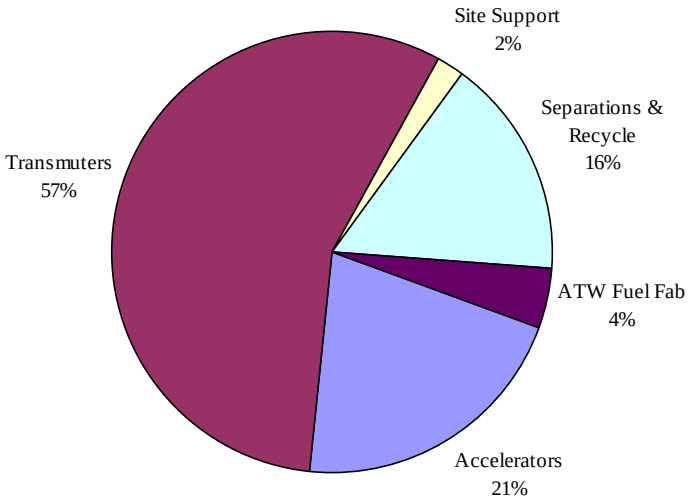


Figure 4.12. Typical Undiscounted Station Capital Costs by Cost Element

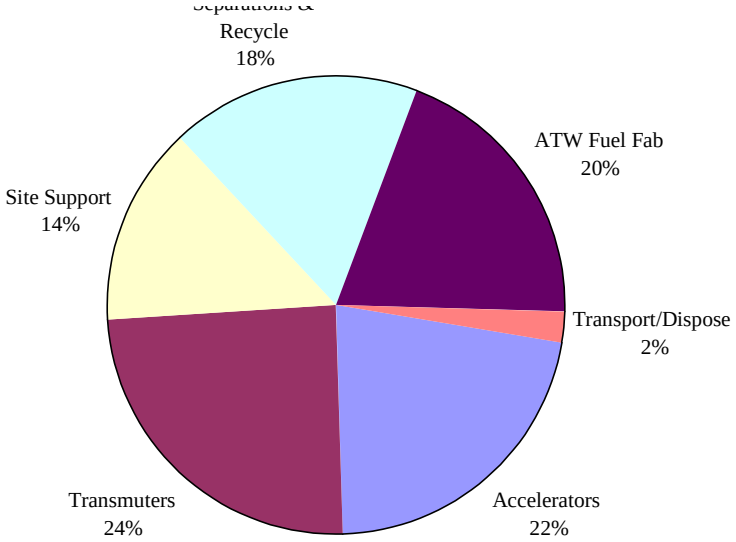


Figure 4.13. Typical Undiscounted Station Operations Costs by Cost Element

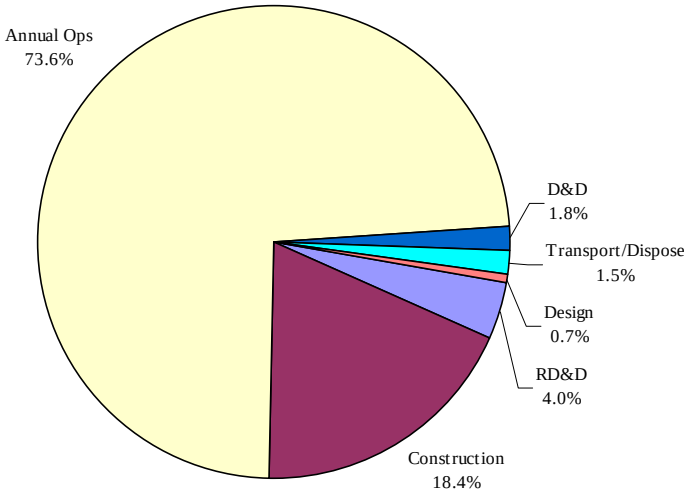


Figure 4.14. Deployed System Undiscounted Costs by Cost Element

Finally, the time distribution of the total undiscounted system life-cycle costs after subtracting the revenue streams resulting from the 43 mills/kWh value assumption is shown in Figure 4.17. The net result is a positive revenue of about $15 billion in undiscounted 1999 dollars for the 43 mills/kWh assumption.

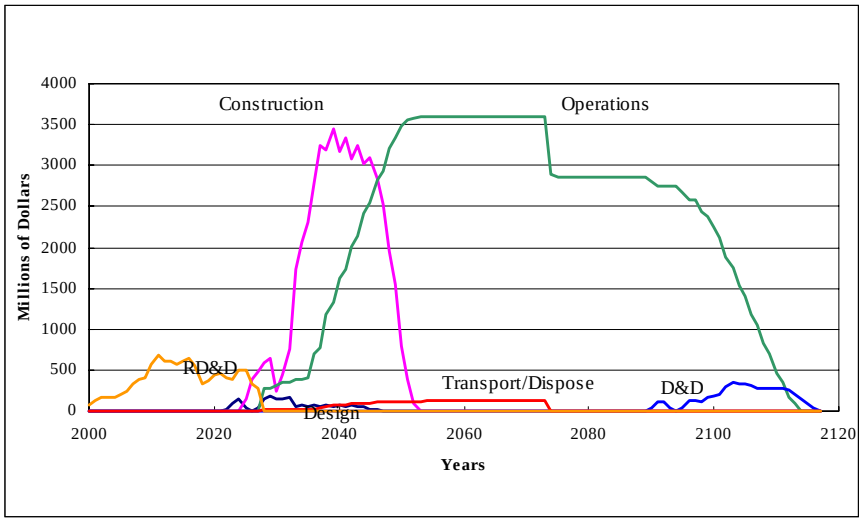


Figure 4.15. Time Distribution of Undiscounted System Life-Cycle Costs by Cost Element

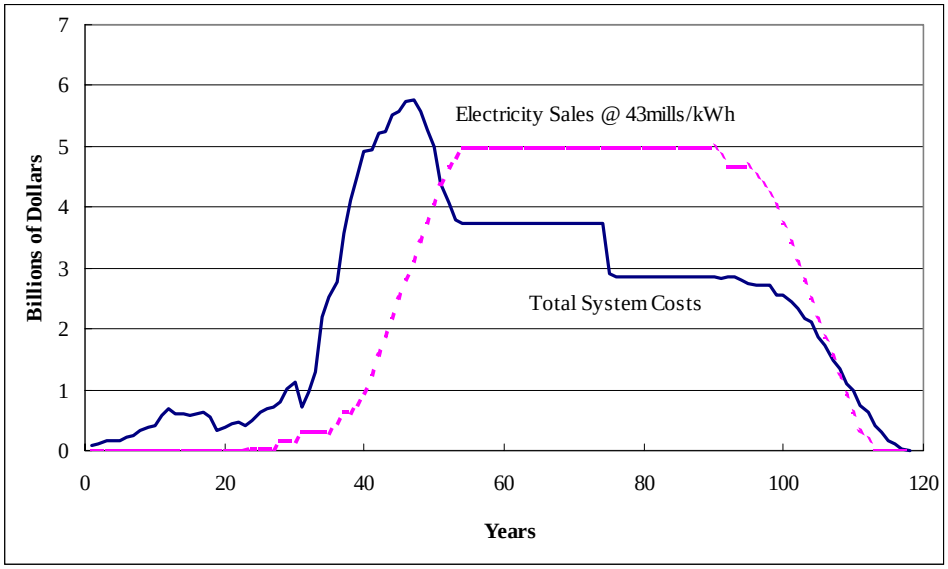


Figure 4.16. Total Undiscounted System Costs and Electricity Revenues as a Function of Time

4.5.2 Net Present Value Analysis of System Costs and Revenues

The undiscounted costs and revenues presented previously in this chapter do not reflect the effects of the time value of money on the expenditure and income streams, which occur over a period of nearly 117 years. To properly evaluate the real economic effectiveness of a project that extends over such a significant period of time, it is necessary to consider the time value of monies spent and received over the project lifetime, i.e., compute the net present values of those future costs and revenues.

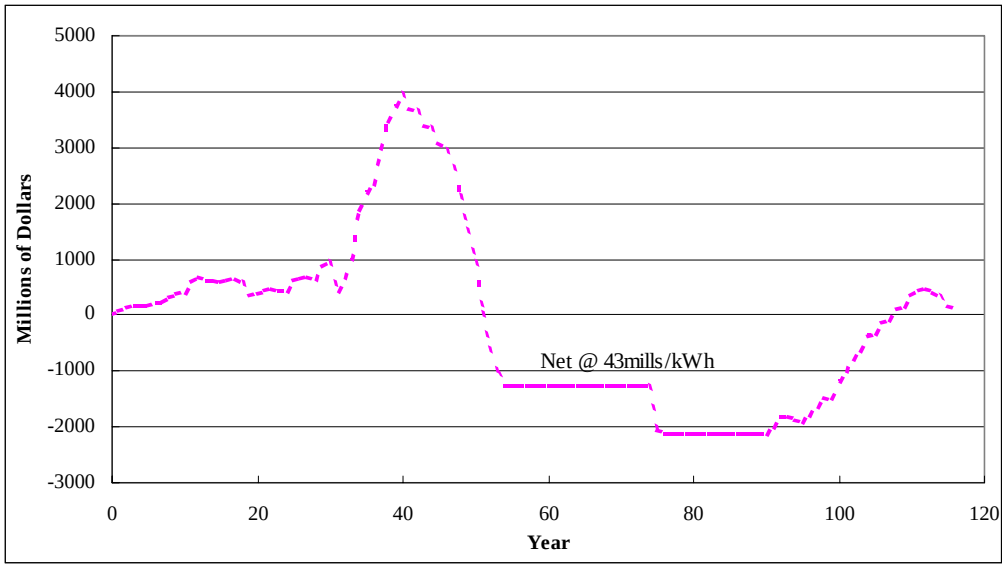


Figure 4.17. Total Undiscounted System Costs Minus Electricity Revenues as a Function of Time

An annual net discount rate of 3% was applied to both the cost and revenue streams. The resulting net present values for the system cost elements and for the electricity revenue stream are summarized in Table 4.25. The discounted system net present value return was found to be -$14.8 billion dollars over the system lifetime, assuming the 43 mills/kWh revenue rate suggested by EPRI, as mentioned earlier.

The cumulative net present values of system cost and system revenue are shown in Figure 4.18, illustrating that the discounted system costs always exceed the discounted revenues over the system lifetime.

Table 4.25. Summary of Estimated Net Present Values of ATW System Life-Cycle Costs (billions of 1999 dollars)

System Element	R&D	Demo	Implementation			Total
			Capital	Operating	D&D	
Accelerators	0.14	1.6	3.5	5.8	0.027	11.2
Transmuters	0.81	1.2	8.9	6.4	0.139	17.5
Separations	0.38	1.3	2.8	7.0	0.042	11.5
ATW Fuel Fabrication	--	0.4	0.6	5.5	0.010	6.5
Site Support	--	0.6	0.3	4.1	0.002	4.9
Retrieve/Transport/Dispose	--	0.04	--	0.8	--	0.9
Integration	0.06	0.6	--	--	--	0.6
Subtotals	1.4	5.7	16.1	29.7	0.2	53.1
Electricity Revenue		0.1		38.1		38.3

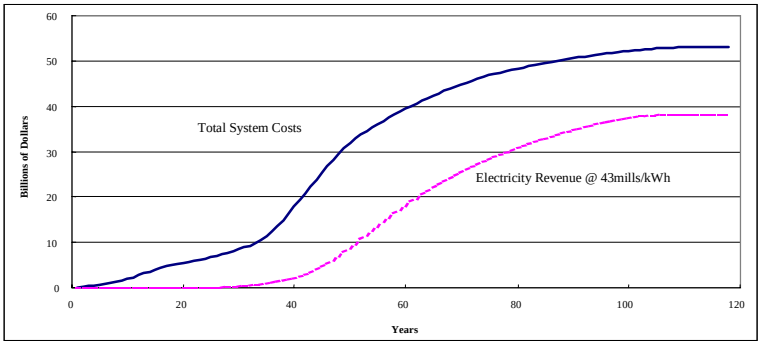


Figure 4.18. System Cumulative Net Present Values of Costs and Revenues

5.0 Uncertainty Analyses

All of the cost elements in the cost analyses presented in Chapter 4 of this report are uncertain by varying amounts because the various facilities have not yet been fully engineered and certainly have not yet been constructed. Thus, the estimated cost for each of these cost elements has a range of possible values. To estimate the magnitudes of these uncertainties and their impact on the ATW system life-cycle cost estimate and on the cost of electricity produced by that system, a Monte Carlo analysis was performed. The estimated base cost for each unit of each cost element and the upper- and lower-bound estimate for each of those costs were used to form a triangular distribution of estimated costs. These distributions were randomly sampled during each history in the Monte Carlo calculation, with the samples used in the ATW System Cost Model to obtain an estimate for the total system life-cycle costs. This cycle was repeated for 10,000 histories in the Monte Carlo calculation to achieve a satisfactory degree of convergence and resulted in a density distribution of estimated life-cycle costs, which was converted into a probability curve for the estimated system life-cycle cost. As a part of the total system cost estimate calculation, similar probability curves were produced for the estimated cost of each of the principal system cost elements, i.e., component capital and operating costs and system capital and operating costs. The resulting probability curves and their associated cost estimates are shown and discussed in subsequent subsections of this chapter.

5.1 Methodology

Detailed designs were not prepared for individual components of the ATW system as a part of the effort to produce a technology roadmap for the *Report to Congress* (DOE 1999). Cost estimates for the principal ATW components were developed by modifying existing cost information that had been generated for facilities that performed analogous functions in other programs, when such information was available. Thus, the estimated capital and operating costs used in this analysis were basically Rough Order of Magnitude (ROM) estimates.

For two components (the first transmuter and the first LWR processing), actual information from analogous facilities (U.S. commercial nuclear stations, THORP LWR reprocessing plant, ALMR processing) was used to establish the range of uncertainty of the cost estimates for those ATW facilities. For the rest of the Station 1 components, an uncertainty range appropriate for a ROM estimate was used for the initial unit (i.e., -20% to +50% of the estimated value after subtracting the original contingency). For the accelerators and transmuters, sufficient changes in design and construction were anticipated between the first and second units that the wide ranges were assigned to the first units, and a range appropriate for a completed Title II design (-5% to +15%) was assigned to the second units. For the third and subsequent units, it was assumed that these units were essentially copies of the second units, and an uncertainty range of -5% to +5% was assigned. This latter range was also assigned to the second and subsequent units of the rest of the components, because it was assumed that these units were essentially copies of the first units. Thus, the costs associated with the next unit would be well understood and similar to the cost of the previous unit. This process was applied to the estimated capital costs of all of the system components.

A somewhat more complex process was applied to the operating costs for the individual system components. As with the capital costs, estimates for the operating costs associated with these facilities should be considered as only ROM estimates. Thus, the estimated base operating cost for the first installed unit of a given component was treated in a manner similar to that applied to the estimated capital costs for the first unit built. The bounds on the cost estimate distribution were set to range from -20% to + 50% of the base estimated operating cost for these units. No further improvement was assumed for subsequent units of the same type built on the same station. For subsequent sites, it was assumed that there was an opportunity to make small improvements in the design or facility layout to reduce the operating costs of the new station. An uncertainty range of -15% to +5% of the operating cost of the component on the previous site was assumed for the first unit built on the next site. All subsequent units on a site were assumed to have the same operating costs.

Anticipated facility and operating efficiency improvements that can be expected over the life of the facilities were taken into account in the uncertainty analysis. A learning curve was applied to the component operating cost estimate after year 4. It was assumed that in any year, operating costs could increase or decrease from the cost experienced in the previous year and that the change was distributed from a maximum of an 85% learning curve to an increase in costs equivalent to a 102% learning curve with a most likely value of no learning taking place. The expected value of such a random variable is a 95% learning curve over the life of the facility.

Because of the need to sequentially construct many similar units, learning curves were used to model the potential for process improvements and/or reductions in capital costs. Learning curves are defined in Appendix B and their use in estimating ATW capital costs is discussed in Sections 4.3 and 4.4 of this report.

5.2 Application of the Methodology to the System Components

An example application of the above methodology to the accelerators in the system is given in this subsection. The system contains 16 accelerators, 2 per station. For accelerator capital costs, the triangular distribution of estimated capital costs for the first accelerator in the first unit of the Monte Carlo calculation is given by

[Base capital estimate w/o contingency] x [80%, 100%, 150%],

where the distribution has zero probability of containing a value less than 80% or greater than 150% of the original estimated value. For the second accelerator, the triangular distribution is defined as [95%, 100%, 115%] of the estimated cost of the previous unit. This reflects the improved confidence in estimating the cost of a second unit, once a unit has been actually built and operated. Because significant changes may occur in the design between the first and second accelerators, a range of uncertainty normally associated with estimates derived from a Title II design were used. For the third and subsequent accelerators, the triangular distribution is defined as [95%, 100%, 105%] of their original estimated values. This smaller range of uncertainty is what can normally be expected for multiple unit construction. Note that because the cost of the previous unit is used as the most probable value of the estimate, the estimate for each successive unit built is highly correlated with the cost of the previous unit.

For the first accelerator, the annual operating costs in the first year were chosen from a triangular probability distribution given by

[Base operating cost estimate] x [80%, 100%, 150%],

where the terms are as previously defined. After year 4, the estimated value arising from the sampling of this distribution is further adjusted year by year over the remaining operating lifetime of the unit to account for learning experience, using a learning curve factor of the form

$$C_i = C_0 [N_i]^{-x}$$

as given in Appendix B, where N_i is the $(5+i)^{th}$ year of operation of that unit. The exponent is obtained from sampling a distribution that ranges over the possible values as described in the previous section. This distribution has the form [83%, 100%, 102%], reflecting the probabilities that operating costs will be reduced or increased, compared to the previous year's costs, each successive year of the operating lifetime of that unit.

The operating costs for the accelerators at the second station in the first year were sampled from a distribution that ranged from 85% to 105% of the initial operating costs of the previous station with the most probable value being the same operating costs. Again, a range of -15% to +5% was used to reflect the potential of learning from previous experience. After year 4, the annual costs were adjusted similar to that described above. The distribution and the sampling for the learning curve factors for each year of operation (after the first 4 years) continues in the same manner as described above for all system components across all stations in the reference deployment scenario.

5.3 Analysis Results

The resulting probability curves for the estimated values of total capital cost and total operating cost for all of the accelerators in the system over their lifetimes are shown in Figures 5.1 and 5.2.

Figure 5.1 shows that there is a 55% probability that the 15 accelerators included in the post-demonstration implementation costs could be built for the $11.2 billion in the base estimate. The $11.2 billion estimate includes a 23% contingency.

Figure 5.2 shows that without allowances for reductions in operating costs due to operational improvements, the reference operating costs are probably significantly overstated in the reference cost estimate.

Similar figures have been developed for all of the cost elements in the system. The probabilities that the actual capital cost of each component will not exceed the estimated cost ranged from about 32% for LWR processing and site-support to about 65% for ATW Fuel Fabrication. As shown in Figure 5.3, there is a 47% probability that the actual capital costs will not exceed the estimated capital cost in the reference cost estimate.

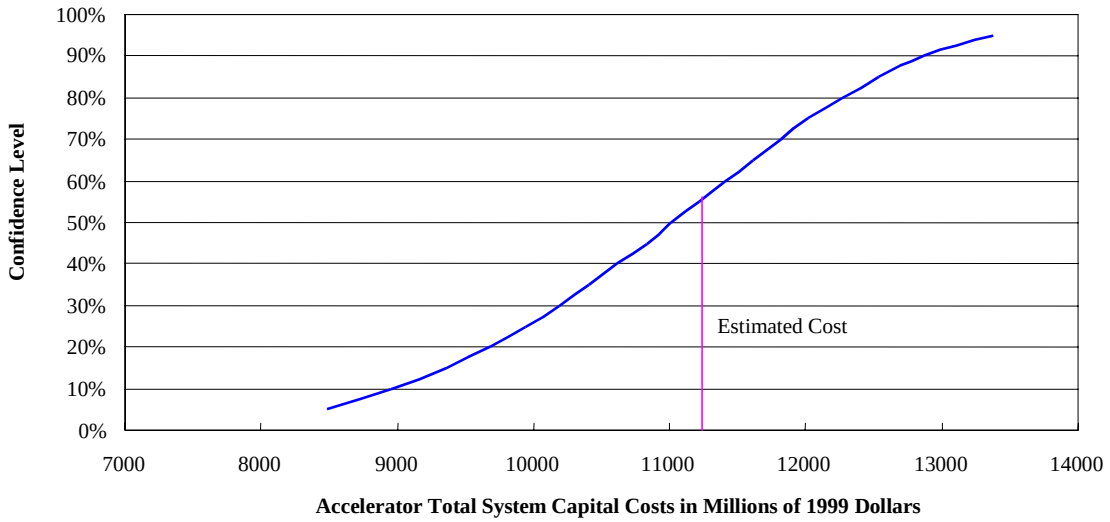


Figure 5.1. Probability that Actual Accelerator Capital Costs Will Not Exceed the Estimated Cost

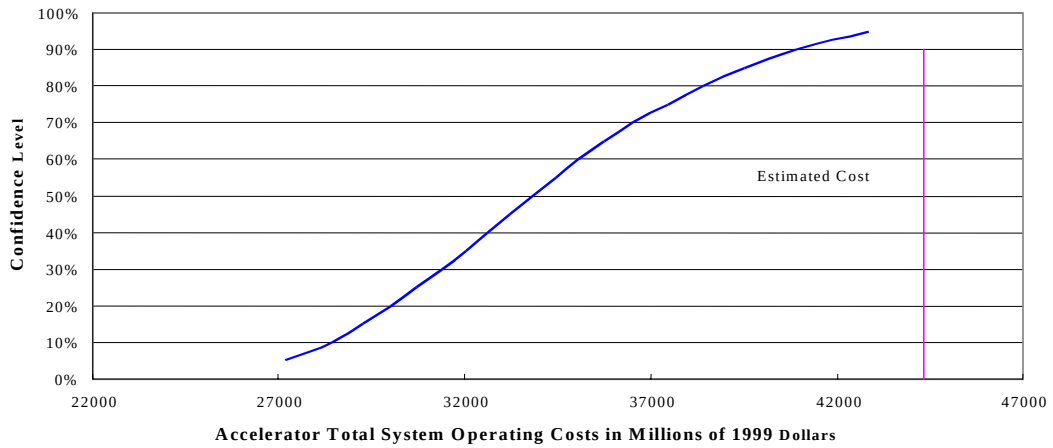


Figure 5.2. Probability that Actual Accelerator Operating Costs Will Not Exceed the Estimated Cost

Figure 5.4 shows that the implementation operating costs are most likely overestimated in the reference case. Although the transmuter and chemical processing operating costs (not shown) used in the reference scenario fell within expected ranges of uncertainty, the overall operating cost in the reference scenario appears to be high when calculated without application of learning curves.

Overall, Figure 5.5 shows that there is a 95% probability that the actual system implementation cost will not exceed the estimated system implementation cost for the reference scenario.

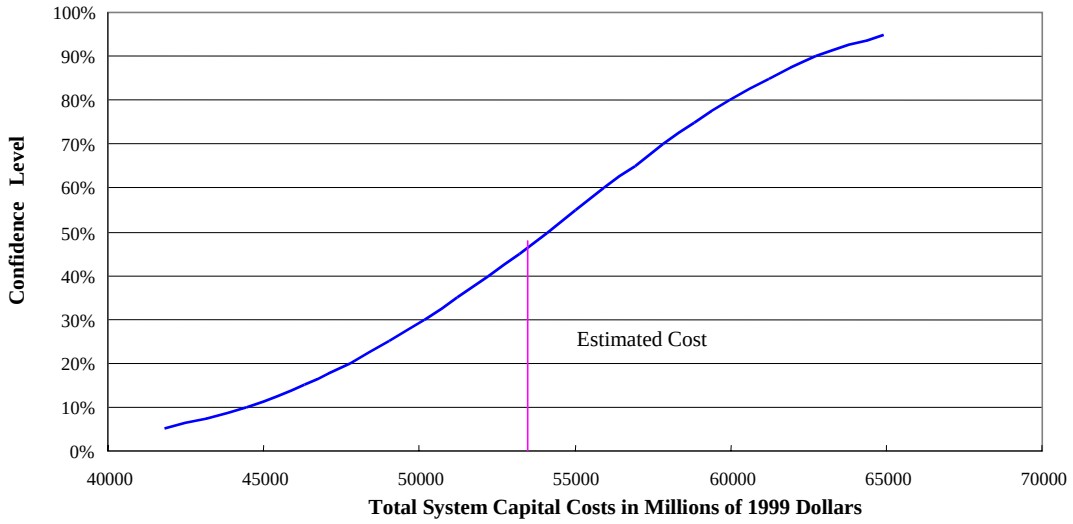


Figure 5.3. Probability that Actual System Capital Costs Will Not Exceed the Estimated Cost

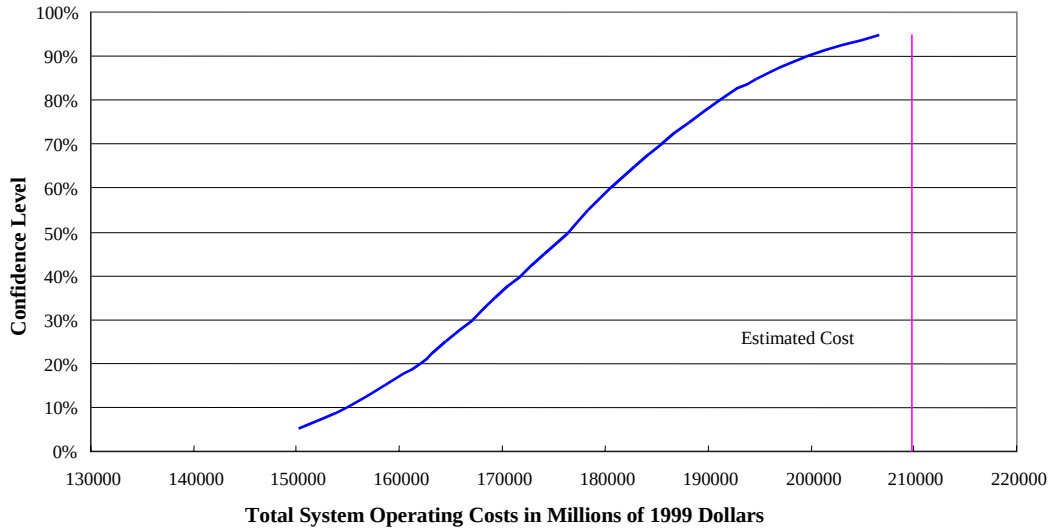


Figure 5.4. Probability that Actual System Operating Costs Will Not Exceed the Estimated Cost

The probability curves for the production cost of electricity in the ATW system in undiscounted dollars, are shown in Figure 5.6 where RD&D costs are included and in Figure 5.7 where RD&D costs are excluded. These curves show that, with a 50% probability, the cost of ATW electricity would not exceed 36.5 mills/kWh and 34.7 mills/kWh.

When the cost and revenue streams are discounted, with a triangular uncertainty distribution of [0%, 3%, 6%] applied each year, the cost of ATW electricity would, with a probability of 50%, be 57.4 mills/kWh when RD&D costs are included (Figure 5.8), and 49 mills/kWh when RD&D costs are

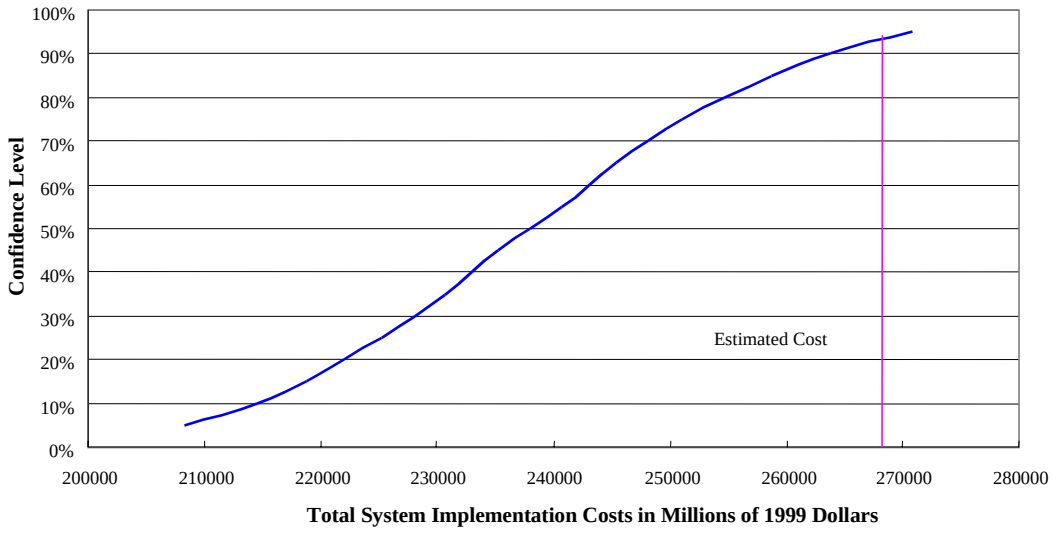


Figure 5.5. Probability that Actual System Implementation Costs Will Not Exceed the Estimated Cost

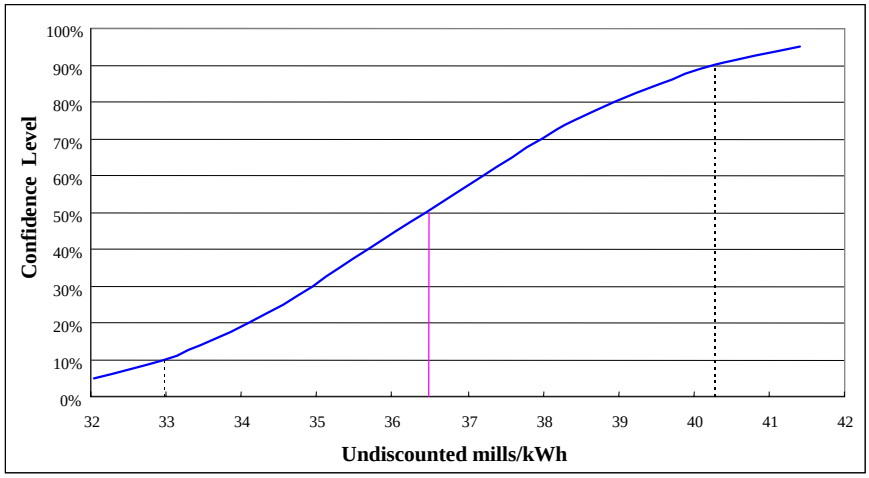


Figure 5.6. ATW Electricity Production Cost Probability Curve, Undiscounted, with RD&D Costs Included

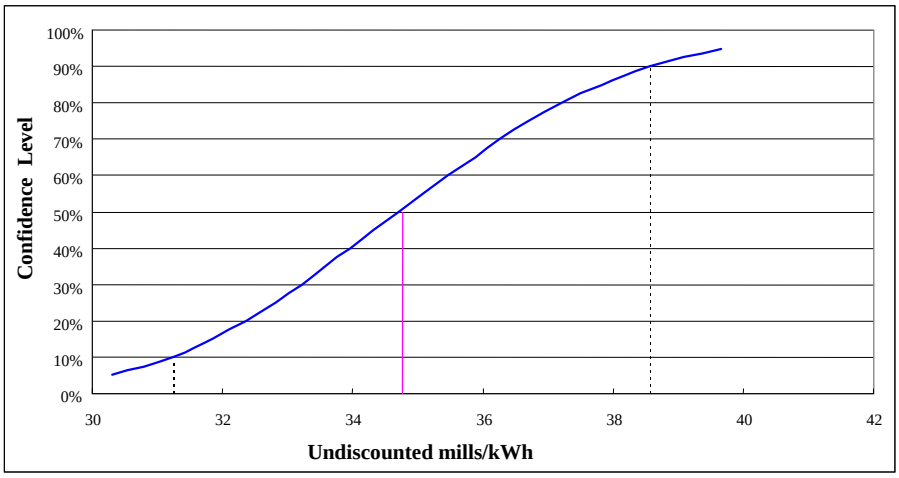


Figure 5.7. ATW Electricity Production Cost Probability Curve, Undiscounted, with RD&D Costs Excluded

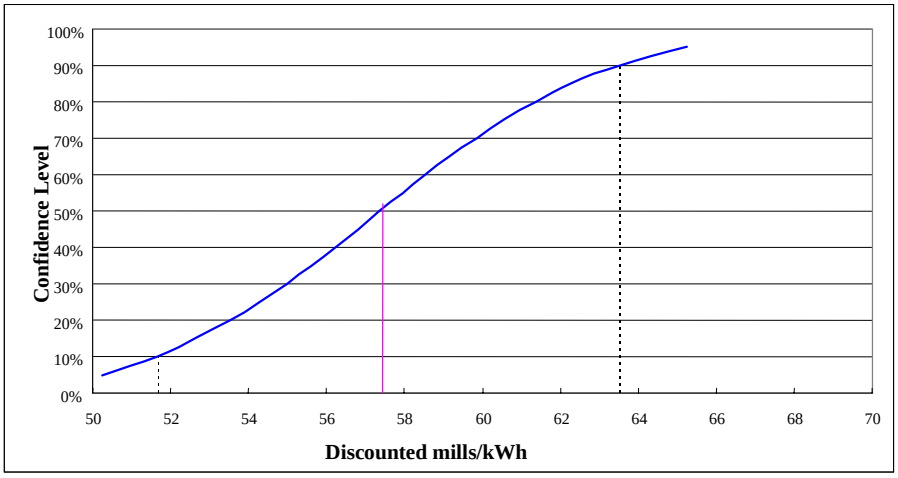


Figure 5.8. ATW Electricity Production Cost Probability Curve, Discounted, with RD&D Costs Included

excluded (Figure 5.9). From Figure 5.9 it is seen that there is less than a 10% probability the ATW system could produce electricity at a rate less than 43 mills/kWh, and about a 90% probability the production costs rate would be less than 55 mills/kWh.

This range is displayed in Figure 5.10 for comparison with the 1996 electricity production costs for investor-owned utilities in the contiguous 48 states of the United States, as discussed in the next subsection.

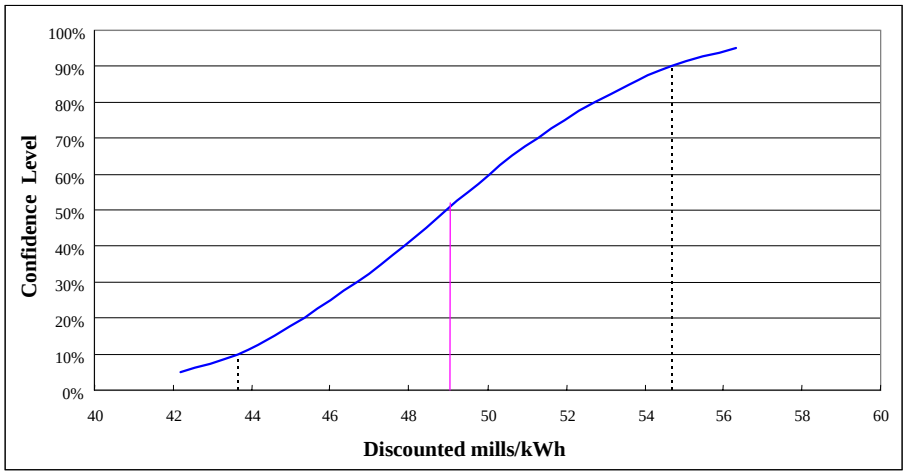


Figure 5.9. ATW Electricity Production Cost Probability Curve, Discounted, with RD&D Costs Excluded

5.4 Production Costs for Investor-Owned Utilities

The electricity production costs for investor-owned utilities for the year 1996 were used to compare to the unit production costs (mills/kW-hr) of the ATW system. The electricity production costs were obtained from data compiled by the DOE EIA (1997) (see DOE EIA website: http://www.eia.doe.gov/cneaf/electricity/invest/invest_sum.html). DOE EIA receives electricity production cost information annually from electricity providers throughout the U.S. The distribution of electricity production costs was developed by adding the power production costs, interest on long-term debt, and depreciation expenses for each investor-owned utility. Production costs for electricity in Hawaii and Alaska were not included in this analysis because the electricity generated from an ATW system would not be utilized in either of these states.

The results of this analysis are shown in Figure 5.10, together with the 10% to 90% probability range of ATW electricity production costs (without the ATW RD&D costs) predicted by the Monte Carlo analysis of the uncertainties in the various elements of cost for the ATW system, as discussed earlier in this chapter. From the figure, it is seen that the range of predicted ATW electricity production costs for discounted cost and revenue streams is higher than the production cost for most of the electricity produced by the investor-owned utilities. Thus, the cost of ATW electricity may significantly exceed that of other commercially produced electricity, and would probably not be competitive with other sources of electric power in the United States.

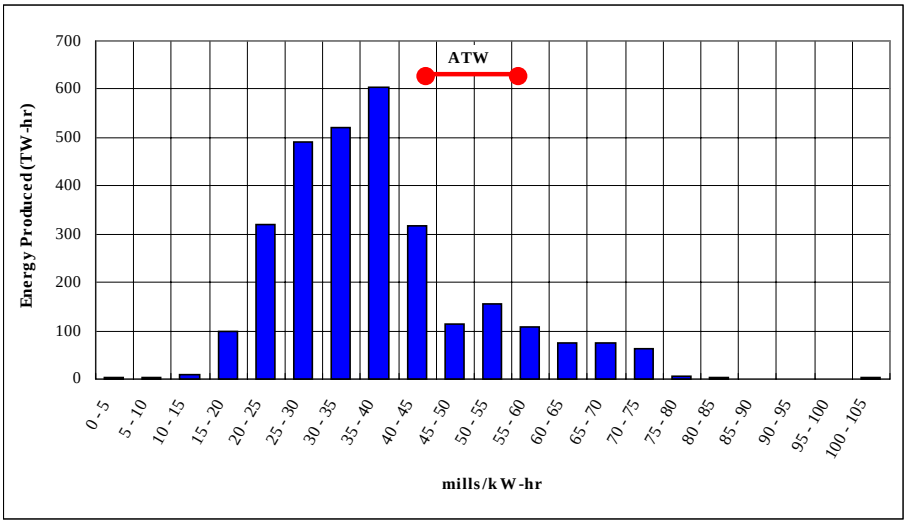


Figure 5.10. Comparison of ATW and Investor-Owned Utility Production Costs

6.0 References

ANL. 1999a. Roadmap for the Development of Accelerator Transmutation of Wastes: System Scenarios. ANL-99/16, Argonne National Laboratory, Chicago.

ANL. 1999b. Preparation of a Technology Development Roadmap for the Accelerator Transmutation of Waste (ATW) System: Report of the ATW Separations Technologies and Waste Form Working Group. ANL-99/15, Argonne National Laboratory, Chicago.

DOE. 1997. Financial Statistics of Major U.S. Investor-Owned Electric Utilities 1996, DOE.EIA-0437(96)/1, Washington, D.C.

DOE. 1998b. Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program. DOE/RW-0510, U.S. Department of Energy, Washington, D.C.

DOE. 1998c. Viability Assessment of a Repository at Yucca Mountain. DOE/RW-0508, U.S. Department of Energy, Washington, D.C.

DOE. 1999. A Roadmap for Developing ATW Technology: A Report to Congress. DOE/S-0129, U.S. Department of Energy, Washington, D.C.

GE. 1995a. ALMR Actinide Recycle System: 1994 Capital and Busbar Cost Estimates. GEFR-00940, GE Nuclear Energy Advanced Reactor Programs, San Jose, California.

GE. 1995b. ALMR Actinide Recycle System: Fuel Cycle Facilities Design Report and Cost Estimates. GEFR-00942, GE Nuclear Energy Advanced Reactor Programs, San Jose, California.

LANL. 1999a. High-Power Accelerator Design for ATW Systems. LA-UR-99-3225, Los Alamos National Laboratory, Los Alamos, New Mexico.

LANL. 1999b. Roadmap for the Development of Accelerator Transmutation of Wastes: Target-Blanket System. LA-UR-99-3022, Los Alamos National Laboratory, Los Alamos, New Mexico.

NRC. 1972. Technology, Safety and Cost of Decommissioning a Reference Pressurized Water Nuclear Power Station. NUREG/CR-0130, U.S. Nuclear Regulatory Commission, Washington, D.C.

NRC. 1998. Report on Waste Burial Charges. NUREG-1307 Revision 8, U.S. Nuclear Regulatory Commission, Washington, D.C.

ORNL. 1993. Cost Estimate Guidelines for Advanced Nuclear Power Technologies. ORNL/TM-10071/R3, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

PNNL. 1999a. Performance Assessment of a Geologic Repository Containing High-Level Waste and Waste from Accelerator Transmutation of Waste (ATW). PNNL-13030, Pacific Northwest National Laboratory, Richland, Washington.

PNNL. 1999b. Estimated Cost of an ATW System. PNNL-13018, Pacific Northwest National Laboratory, Richland, Washington.

Appendix A

Historical DOE Construction Cost Escalation

Appendix A

Historical DOE Construction Cost Escalation

January 1999 Update
Departmental Price Change Index, FY 2001 Guidance
Anticipated Escalation Rates, DOE Construction Projects and Operating Expenses

Rates through 1999 are Historical

Year	Nuclear & Energy Research	Fossil	Conservation & Solar	Defense Programs, EM & General Construction
1976	6.1	6.0	5.7	5.2
1977	6.2	6.3	6.0	6.0
1978	7.1	7.3	6.8	7.3
1979	9.1	9.6	9.1	8.9
1980	9.7	10.1	10.7	9.7
1981	9.2	9.4	9.1	8.1
1982	6.8	6.6	6.5	6.3
1983	3.0	2.6	2.9	3.1
1984	2.4	2.2	2.4	2.4
1985	2.1	1.9	2.0	1.6
1986	1.3	0.6	1.3	1.1
1987	1.9	1.8	1.8	1.8
1988	4.0	4.7	4.0	3.2
1989	4.2	4.4	4.5	3.2
1990	2.8	2.3	2.9	2.3
1991	3.1	2.6	3.0	2.3
1992	2.2	1.6	1.8	1.5
1993	2.6	2.4	2.5	2.2
1994	3.0	3.0	2.8	2.7
1995	3.4	3.9	3.7	2.8
1996	2.0	1.9	1.9	2.4
1997	2.1	1.9	1.8	2.9
1998	2.0	1.9	1.8	2.4
1999	1.6	1.1	1.4	2.3
2000	2.4	2.1	2.2	2.3
2001	2.5	2.5	2.5	2.3
2002	2.6	2.6	2.5	2.4
2003	2.8	2.7	2.6	2.8
2004	2.8	2.8	2.7	2.9
2005	2.9	2.8	2.7	2.9
2006	2.8	2.8	2.7	2.8
2007	2.8	2.7	2.7	2.8
2008	2.8	2.7	2.7	2.8
2009	2.9	2.7	2.8	2.8

Appendix B

Application of Learning Curves to Cost Estimation

Appendix B

Application of Learning Curves to Cost Estimation

A phenomena well known to industrial engineers and costs estimators is the effect of worker learning and process improvement on production rates when the same or similar operations are performed repetitively. A fairly detailed discussion of this subject is given in McNeill and Clark (1966), and in a variety of similar sources. Much learning curve data is derived from operations such as automobile assembly and aircraft assembly, but the basic theory is generally applicable to any kind of complicated task that is repeated a significant number of times. Most manufacturing firms gather data from their production operations and analyze the data to determine the actual rate of reduction of cost as the number of units produced increases.

In general, the cost per unit of production decreases in a non-linear manner. The mathematical expression for this phenomena is given by

$$C_i = C_0 \, [N_i]^{-x} \quad \text{or} \quad C_i / C_0 = [N_i]^{-x}$$

where C_i is the reduced cost of the unit, C_o is the cost to produce the first unit, N_i is the sequential number of the unit that was produced for the cost C_i, and X is the exponent that expresses the rate at which the production cost is decreasing (i.e., the experience curve). The experience curves are usually described in terms of the percent of decrease between the first and second units. For example, if the cost of unit 2 is only 85% of the cost of unit 1, then that unit is said to be on an 85% learning curve. The cost of unit 4 will be 85% of unit 2, and so on, for each doubling of the number of units produced. The value of the exponent X can be determined by solving the above equation for X.

$$X = - \log (C_i/C_0) / \log N_i$$

When the cost ratio is 0.85, X = 0.23446. When the ratio is 0.95, X = 0.07400, and so on. Thus the cost reduction factor for a 95% learning curve is $N^{-0.0740}$.

In the analyses of design, construction, and decommissioning cost for the replicated units deployed in the full-sized ATW system in this report, the second or NOAK unit costs were reduced from the initial unit cost using 95% learning curve factors for all units except the accelerators, which were reduced using 85% learning curve factors.

B.1 Reference

McNeill, T. F., and D. S. Clark. 1966. *Cost Estimating and Contract Pricing*, American Elsevier Publishing Company, Inc., New York.

Appendix C

Application of Scaling Factors to Cost Estimates

Appendix C

Application of Scaling Factors to Cost Estimates

Many times when making rough order-of-magnitude estimates of the cost of constructing a new facility, cost estimates will already exist for a facility with the same basic functions as the one to be estimated but with a larger or smaller production capacity. In those instances, a general rule of thumb exists for scaling the original estimate (or an actual cost) to reflect the different production capacity of the proposed new facility. That rule of thumb can be expressed by the following equation:

$$C_n = C_o \, (K_n / K_o)^{0.6}$$

where C_n and K_n are the estimated cost and the planned capacity, respectively, of the proposed new facility, and C_o and K_o are the cost and capacity, respectively, of the facility for which a cost estimate (or an actual cost) is available. The closer the capacity ratio is to unity, the better the scaling factor will approximate reality.

The cost of the reference facility, C_o, must be escalated to dollars of the same year as the year for which the scaled estimate is desired. In this report, the Department of Energy escalation indices for Nuclear & Energy Research, given in Appendix A, were used.

In the analyses in this report of construction cost of facilities for which cost estimates existed for similar types, the 0.6 scaling factor was used to estimate the cost of the new facilities. Similarly, the operating and maintenance costs for such a new facility were estimated from the operating and maintenance costs of the reference facility, also using the 0.6 rule.

Appendix D

ATW Program Development and Deployment Scenarios and Schedules

Appendix D

ATW Program Development and Deployment Scenarios and Schedules

D.1 Overview

The main objective of the ATW Program is to transmute 86,317 MTU of commercial light water reactor (LWR) spent nuclear fuel into waste material with lower levels of radioactivity and less heat rejection. This can be accomplished in a phased program that begins with government support and is completed by deployment of facilities by project privatization. The key phases of the program are shown on Figure D.1 and are defined as follows:

- Government-Supported Phase (2000 to 2027)
  - -- R&D Phase (2000 to 2008)
  - -- R&D Follow-Up Phase (2008 to 2027)
  - -- Demonstration Phase (2000 to 2027)

- Privatization Phase (2023 to 2111)
  - -- FOAK (first-of-a-kind) Plant Privatization (2023 to 2097)
  - -- NOAK (nth-of-a-kind) Plant Privatization (2027 to 2117).

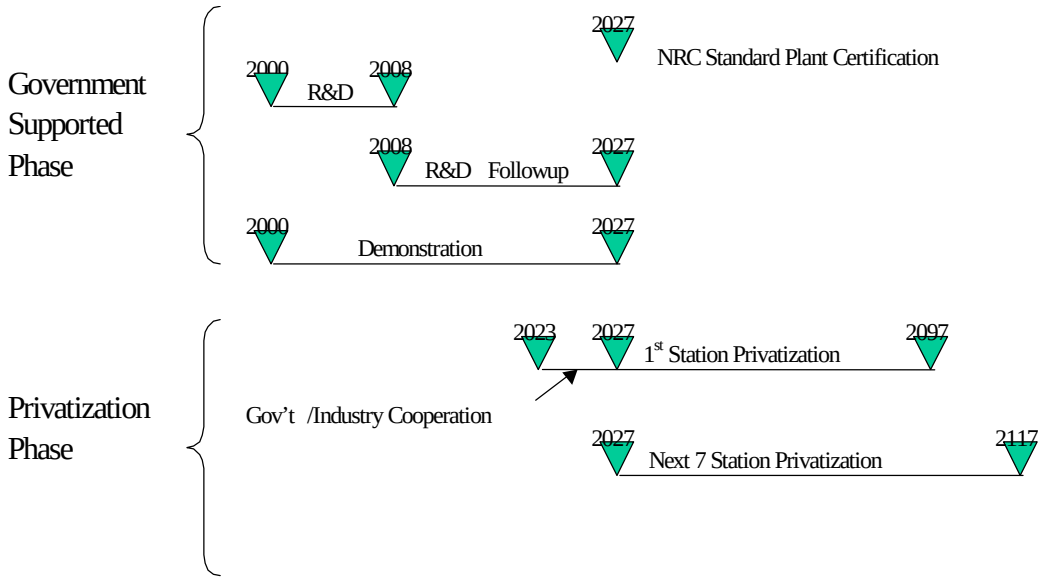


Figure D.1. ATW Program Phases

Summary descriptions of the Government-Supported Phases are provided in Section D.7. All schedule dates are based on the start of the fiscal year, unless otherwise noted.

D.2 Station Configurations for the Demonstration Phase and Station Privatization

The schedule is based on the phased construction and startup of the ATW transmutation/power complex (accelerator/transmuter/steam generator/turbine generator) and the phased construction and startup of the Fuel and Target Facility (FTF). This phased construction and startup forms the basis for all the other activities on the Demonstration Phase and Station Privatization schedules.

D.2.1 ATW Transmutation/Power Complex

The phased construction of the Demonstration Transmuter through its progression from low-power operation to full-power operation, the addition of the second transmuter to form the first (FOAK) power block, the addition of the second (FOAK) power block to form the first half station, and the addition of two NOAK Power Blocks to complete the first station, is shown in Figure D.2. A total of four Power Blocks (eight transmuters) will generate 2480 MWe of electricity and transmute about 1800 kg of TRU per year at equilibrium operation.

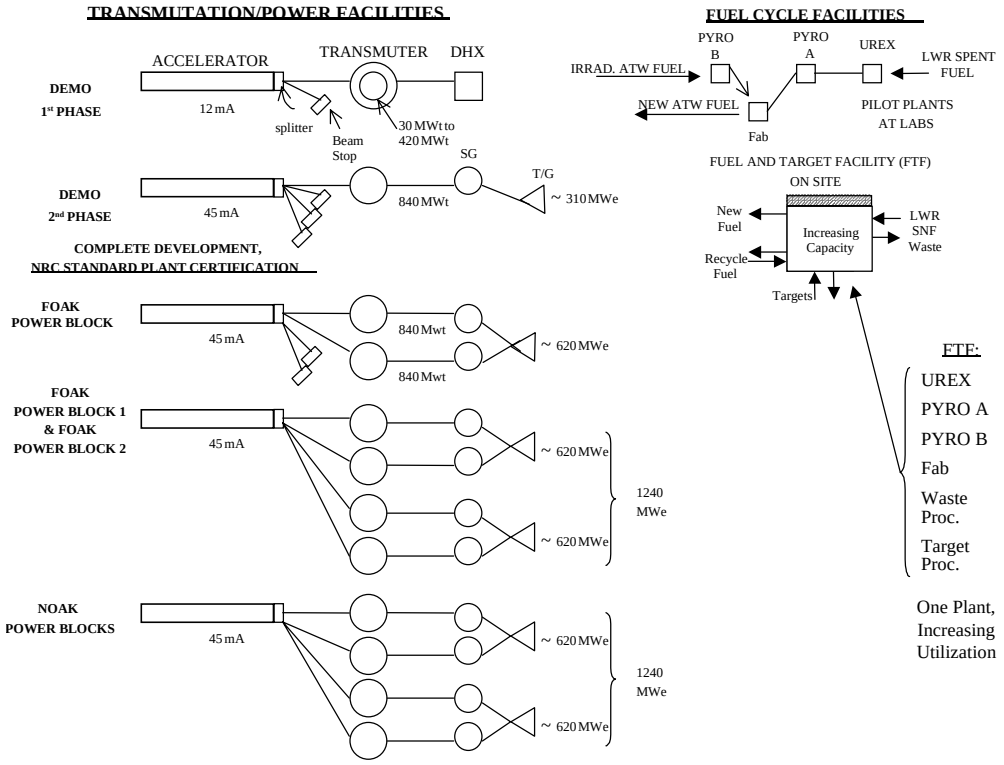


Figure D.2. ATW Phased Configuration at First Station

The first facility to be built on the site will be the Demonstration plant. This initial part of Station 1 will use a full-size accelerator with only enough power supplies to produce a 12-mA proton beam. The beam will produce transmutation within a 30-MWt fuel core placed within a full-size transmuter vessel, which will provide for controlled tests with relatively low power levels to demonstrate the feasibility of the system. A full-size accelerator structure will provide a cost-effective approach to building the full power (45-mA) machine by the later addition of power supplies, thereby eliminating the need for a separate small-scale accelerator for the 30-MWt tests. Similarly, a full-size transmuter vessel will be used for the demonstration tests to avoid the cost of a separate small vessel and related components and systems. With the use of sodium coolant, the 31-foot diameter, 840-MWt reactor vessel used on the Advanced Liquid Metal Reactor (ALMR) project was selected as the reference baseline design for ATW. The major components (primary pumps, intermediate heat exchangers, piping, decay heat-removal systems, refueling systems [with modifications] and other features) of the ALMR plant are also referenced, based on the advanced stage of development and suitability to the ATW project. For the demonstration tests, these systems will be operated at reduced capacity. An intermediate sodium loop will be connected to a dump heat exchanger (DHX) for cost-effectiveness and simplicity of operation. Similar to the ALMR, the transmuter vessel will be mounted on a seismically isolated platform. The beam tube from the accelerator will enter the transmuter vessel through the head, requiring modification to the head area, the fuel handling equipment, control rod drives, instrumentation, etc. A beam splitter and beam stops will be provided to begin tests on the splitter.

Following operation at 30 MWt, the fuel core will be incrementally increased in size to permit increasing power output in steps up to 420 MWt (this is approximately the size of FFTF, which successfully used DHXs [sodium to air]). After completion of the 420-MWt demonstration tests, the unit will be shut down for addition of the turbine-generator systems and removal of the DHX.

The demonstration plant will be upgraded by increasing the accelerator beam current from 12 mA to 45 mA by adding power supplies, by increasing the 420-MWt fuel core size to 840-MWt, by adding a full-size 840-MWt steam generator, and a full-size 620-MWe turbine that will be operated at half-power to produce 310 MWe. Splitters and beam-stops will be added to the accelerator system to permit its operation at full power and to demonstrate splitting of the beam between four locations (to simulate four transmuters—the full-scale configuration of a one-half station). The helical coil steam generator (HCSG) has been successfully tested at 76 MWt for 16,000 hours, and other components of the system have been tested, but R&D needs to be completed before startup of this full-scale “ALMR equivalent” system. Successful operation of this prototype will be the basis for the NRC Standard Plant Certification in 2027 and the start of privatization of the remaining power blocks on the first station site.

The next step is to add another transmuter and steam generator to complete the FOAK Power Block. This power block will supply sufficient steam to the single 620-MWe turbine-generator to produce 620 MWe, which is the same size power block used in the ALMR program analyses.

Next, the first FOAK Power Block will be added to complete the first half of a four-power block station. The four transmuters in these two power blocks will be driven by the first 45-mA accelerator and 1240 MWe will be produced.

The second one-half station (two NOAK Power Blocks) will then be built, consisting of one accelerator, four transmuters, four steam generators, and two turbine generators. An additional 1240 MWe will be produced, and the full station will produce 2480 MWe.

D.2.2 Fuel and Target Facility and Pilot Plants

The fuel supply for the demonstration plant will be provided from the pilot plants at the national laboratories and possibly other government sites. In the reference design, the pilot plants will process the incoming LWR spent nuclear fuel in an aqueous process (UREX) to separate the uranium and produce an oxide transuranic (TRU) product, followed by a pyrochemical process (Pyro A) to convert the oxide to metal and separate the fission products. The metallic TRU product will be fabricated into ATW metal fuel assemblies in a fabrication facility, then shipped to the demonstration plant at the government site. Irradiated ATW fuel will be returned to the pilot plants and processed in a separate pyrochemical process (Pyro B) to remove the fission products. The recycled TRU will be mixed with additional fresh TRU feed material from the LWR processing function and fabricated into reload ATW fuel assemblies. All the above processes are accomplished within remotely operated hot-cell facilities.

A full-size FTF will be built on the same site as the FOAK accelerator and transmuter facilities (Figure D.2). The FTF will include the UREX, Pyro A, Pyro B, fuel fabrication, waste processing, target fabrication, and target processing functions, which results in a fuel-cycle facility that receives the LWR spent nuclear fuel at the site where it will be transmuted, with no shipments of fuel material from other sites required. The integration of all of the fuel processing functions into a single structure is a major factor in providing suitable safeguards for this material. The waste streams from the FTF will be packaged and shipped to their respective long-term storage or disposal locations. These streams include the high-level fission product and irradiated metal wastes returned to the high-level waste (HLW) repository at Yucca Mountain and low-level waste (such as the uranium) sent to a low-level waste site.

The FTF building will be sized to support the operation of eight transmuters on the first 2480-MWe station. The equipment will be provided in phases to support the phased construction of the ATW transmuters. It will supply some of the fresh fuel for the 420-MWt Demonstration Plant and all of the fresh fuel for all subsequent power block startups and operation. The large quantity of fresh fuel from the UREX and Pyro A sections of the FTF requires that this section be run at full-capacity following a short ramp-up, to build up an inventory of fresh fuel material, while keeping the size of this section of the FTF as small as possible. Fresh fuel from the Station 1 FTF will also be used to start up the first power block at the next station. Equipment for the Pyro B, fuel fabrication, waste processing, and target processing portions of the FTF may be installed in phases as the successive power blocks are built and operated, to be cost-effective. The same design of the FTF will be provided at each successive station.

D.2.3 Station Privatization

The station privatization schedule is based on deployment of successive station configurations as shown in Figure D.3. Each station will utilize cross-connected beam tubes such that each transmuter in a power block is driven with protons from a different accelerator on the site to avoid shutting down an

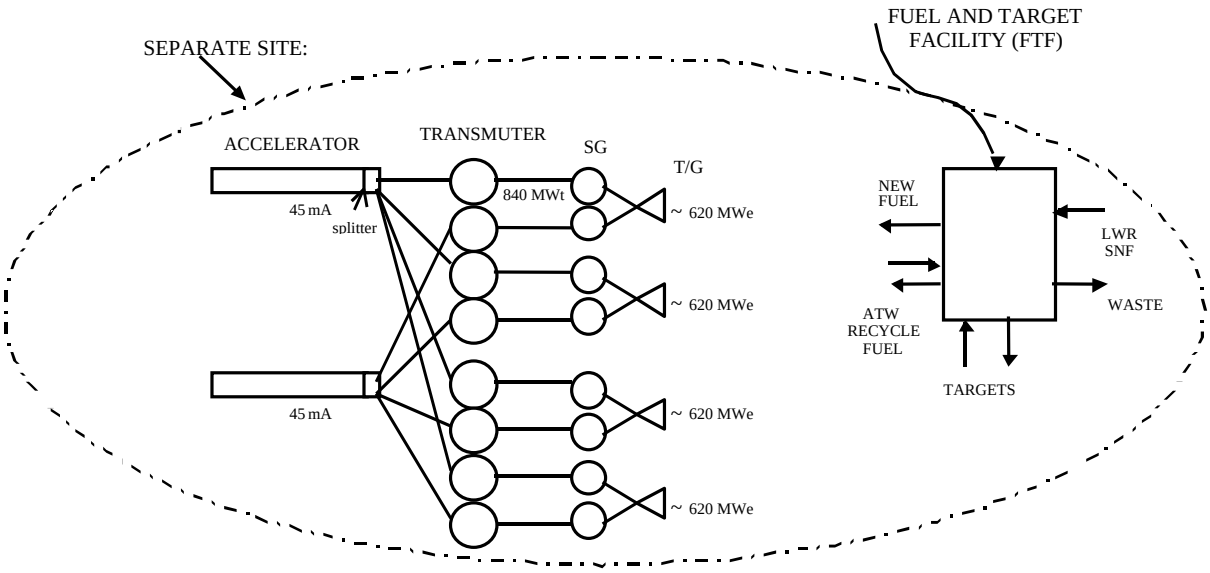


Figure D.3. ATW Full Configuration NOAK Plant (2480 MWe)

entire power block in the event of an accelerator shutdown, thereby increasing the reliability of the electrical output of the station. This approach will reduce concerns about a potentially interruptible power supply, ensure receiving the best possible payment for the electricity delivered to the grid, and will achieve a high throughput for transmuting the LWR spent nuclear fuel.

D.3 Summary Description of Project Phases and Summary Schedules

This section provides summary descriptions of the project phases to provide an overview of the work to be performed with additional detailed description provided in Section D.7 of this appendix. This section also identifies the summary level schedules for the several phases of the project.

D.3.1 Summary Level Schedules

The general activities and milestones for all phases of the program are shown in Figure D.4. The Government-Supported Demonstration Phase of the project is scheduled in Figure D.5 and the accompanying milestone definition is shown in Figure D.6. Included are the R&D Phase, R&D Follow-Up Phase, and the Demonstration Phase, all resulting in the key milestone of obtaining an NRC Standard Plant Certification for the ATW plant and the FTF. A detailed schedule of the Government-Supported Phase of the project is provided in Section D.7 of this appendix.

The Privatization Phase of the project begins with the second power block on Station 1. The NRC Standard Plant Certification and the successful operation of the Demonstration Power Block can be the basis for privatizing the design, construction, procurement, and licensing of the rest of the power blocks at the first station and all of the power blocks at subsequent stations.

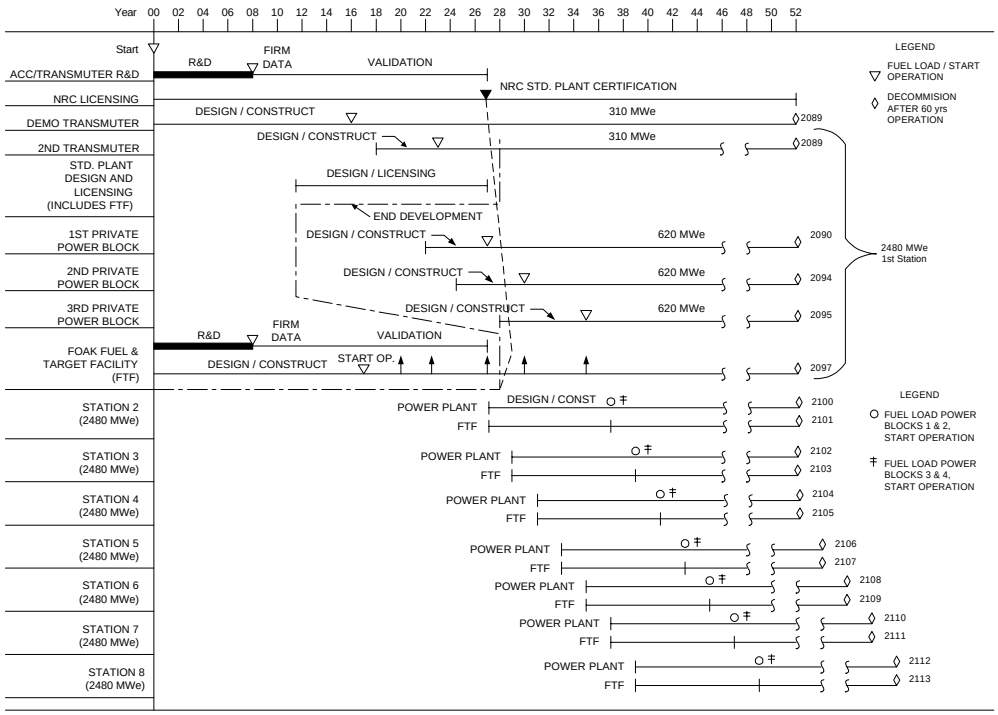


Figure D.4. Total Project Schedule

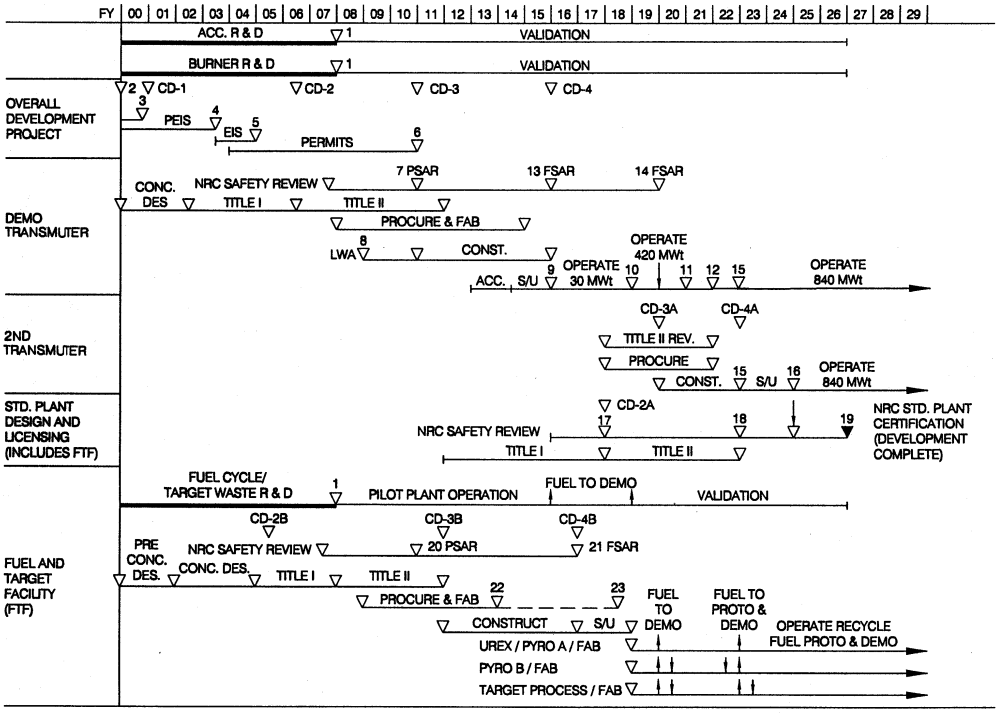


Figure D.5. Level 0 Schedule to Complete Demonstration

Milestone **Description**

1. Decide final technology (01/2008)
2. Project start (01/2000)
   CD-1 Approve Mission Need (01/2001)
   CD-2 Approve Title I Baseline, start Title II, Demonstration (03/2006)
   CD-3 Approve Construction (Demonstration) (01/2011)
   CD-4 Approve Operation (Demonstration) (01/2016)
3. Mission Analysis/Need (10/2000)
4. ROD from PEIS, select site (03/2003)
5. Complete Facility/Site EIS (01/2005) – all facilities
6. Complete Permit Approval (01/2011) – all facilities
7. NRC Approve PSAR (01/2011), Demonstration (01/2009)
8. Receive Limited Work Authorization, start site work
9. Fuel Load/Startup/Operate at 30 MWt (01/2016)
10. Fuel Load/Startup/Operate up to 420 MWt (01/2019)
11. Complete 420 MWt tests (01/2021)
12. Shutdown, Prepare for 840 MWt (01/2022)
13. NRC Approve FSAR (Demonstration and FTF) (01/2016)
14. NRC Approve update FSAR (Demonstration) (01/2020)
    CD-3A Approve Construction 2nd Transmuter (01/2020)
    CD-4A Approve Operation 2nd Transmuter (01/2023)
15. Fuel Load/Startup/Operate Demonstration Transmuter at 840 MWe (01/2023)
16. Demonstration test report to NRC (01/2025)
    CD-2A Approve Title I Baseline, Start Title II (Standard Plant) (01/2018)
17. Start NRC Review Standard Plant PSAR (01/2018)
18. Start NRC Final Review Standard Plant FSAR (01/2023)
19. NRC Issue ATW Standard Plant Certification
    CD-2B Approve Title I Baseline, Start Title II (FTF) (03/2006)
    CD-3B Approve Construction (FTF) (01/2012)
    CD-4B Approve Operation (FTF) (01/2017)
20. NRC Approve PSAR (01/2011) – FTF
21. NRC Approve FSAR (01/2017) – FTF
22. Procure/Fabricate equipment for Prototype/Demonstration Support (01/2014)
23. Procure/Fabricate equipment for FOAK Plant Support (01/2019) as required.

Figure D.6. Milestone Descriptions for Level 0 Schedule to Complete Demonstration

The ALMR program schedule was based on receiving the NRC Certification 23 years after project start, building on many earlier years of development. The ATW program schedule assumes completing the demonstration 27 years after project start, assuming the use of sodium coolant and ALMR similarities. Other programmatic similarities between the ALMR program and the ATW program include the R&D of similar metallic fuels, similar pyroprocess systems, similar sodium coolant components, and the design and construction of an on-site Fuel Cycle Facility that minimizes offsite shipment of nuclear fuel. The schedule for the 2480-MWe NOAK station (four 620-MWe Power Blocks) from the start of the final design to first fuel load in the first transmuter is 10 years. This period is slightly more conservative than the 7-1/2 year similar activity for the 1860-MWe ALMR commercial plant (three 620-MWe Power Blocks), but is reasonable for the current stage of the ATW project.

D.3.2 R&D Phase (2000 to 2008)

This phase includes the basic R&D that will result in firm data being supplied to the design and procurement of demonstration and prototype plants. These efforts include R&D for the accelerator and target/blanket systems and components, including fuel, and the R&D for the fuel cycle development and target development work that will be performed mostly by the national laboratories, with possibly some international cooperative support. This completion date is based on firm data for the reference baseline technology (sodium coolant) as discussed in Section D.7.1.

D.3.3 R&D Follow-Up Phase (2008 to 2027)

This phase provides for pilot plant operations in modified existing facilities, plus support in the design, procurement, construction, startup, and licensing of the ATW Demonstration Plant, the ATW Prototype Plant, the ATW FOAK Power Block, and the FTF. Support will also be provided during the NRC licensing process. This is further discussed in Section D.7.2.

D.3.4 Demonstration Phase (2000 to 2027)

This phase provides for the preparation of Environmental Impact Statements; Permits; Safety Analysis Reports; and design, procurement, construction, and startup of the FOAK facilities to be built on the first government site. Facilities include one accelerator to supply protons to the ATW Demonstration Plant, the ATW Prototype Plant, and the ATW FOAK Power Block. Activities also include all the same steps required to start up the FTF on the site. The primary objective of the Demonstration and the overlapping R&D and R&D Follow-Up Phases is to demonstrate that all segments of the systems are functioning safely and efficiently so that an NRC Standard Plant Certification can be achieved by the end of 2027 to permit privatization to occur. The Demonstration Phase is discussed further in Section D.7.3.

D.3.5 Privatization Phase (2023 to 2111)

As shown on the schedules in Figure D.5, privatization can begin with the operation of the Demonstration Power Block in 2028, after 1 year of full-power operation. At the end of 2027, the NRC Standard Plant Certification will be issued. Private firms should come aboard as operating partners with the DOE contractor operators when the second transmuter is loaded with fuel and started up in 2023, then fully take over at the end of 2027. Privatization of the FTF can also begin in 2028, with firms coming aboard on 2023 as operating partners with the DOE contractors running the FTF at that time. NRC Standard Plant Certification will include the FTF Standard Plant Certification.

Privatization will continue at the first government site for the completion of design, procurement, construction, and startup of the second, third, and fourth power blocks. These blocks will add 1860 MWe (beyond the 620 MWe from the first power block) in a cost-effective manner by utilizing the full potential of the first government site and all the support facilities and infrastructure of the site. While Power Blocks 2, 3, and 4 would be designed and built at the cost of the private firms, the cost of Power Block 1 is covered by the government, along with the cost of the FTF.

The schedule provides for the fuel load and startup of Power Block 2 in 2031, based on the start of Title II for this unit in 2023, a 5-year construction period, and new contracts for construction with the same companies that constructed the Demonstration Power Block. Title II reflects an update of designs to incorporate 4 years of operating information from the Demonstration Power Block. Procurement is assumed to be an extension of orders previously placed, with new contracts written with the same suppliers that were used previously. Power Block 2 will produce 620 MWe.

The schedule provides for the startup of Power Block 3 in 2035 and Power Block 4 in 2036. It is assumed that all contractors used for Power Block 2 will be used on Power Blocks 3 and 4. Construction will be continuous on the site for all three Power Blocks, and procurement will also be continuous to provide for cost-effective manufacturing of components and shop-fabricated plant modules. The four power blocks of Station 1 (2480 MWe) will be operated for 60 years following the end of the demonstration phase and then be decommissioned. Private firms will continue to operate the FTF at increasing capacity to meet the fuel and target demands of Power Blocks 1, 2, 3, and 4 over the next 60 years, then decommission the plant.

Private firms will be responsible for continuously meeting all NRC safety and licensing criteria and requirements and for meeting all safeguards requirements and operating permit requirements. NRC approval for the PSAR and FSAR for Power Blocks 2, 3, and 4 (for construction and operation) will be based on the private firms being the applicants. NRC approval of the private firm as the operator of Power Block 1 will be required. Title II design for Power Block 2 will start in 2023 to permit submittal of the PSAR amendments to NRC as the new plant owner/operator (applicant) to permit NRC approval of the PSAR by start of construction (2026).

Considerable work (not shown on the schedule) is needed to prepare for privatization of Station 1 and the subsequent stations, including defining risks and how to mitigate them, financial incentives, institutional issues, etc. The ATW project office will work with DOE to initiate discussions with the private sector within a few years after the start of the ATW project.

Based on NRC Standard Plant Certification and the continuation of construction and operation of Station 1, the private sector can begin to deploy the next seven stations at various sites around the country. At 2480 MWe for each ATW plant, and an operating time of 60 years, a total of ~5,950 gigawatts electric will be generated by the seven stations. The private sector will decommission all private stations.

D.4 Key Assumptions

Key assumptions used during the preparation of these ATW roadmapping schedules are:

- The reference baseline technology as described in Section D.7.1 will be selected at the 2008 decision point, with firm data for design and procurement at that time.

- The Demonstration Power Block and the three additional Power Blocks will be built on one site, along with its associated FTF. The schedule reflects any government site.

- Sufficient funds will be available on 10/01/1999 to prepare Mission Need and Mission Justification documents to reach CD-1 by 10/01/2000 (approval of Mission Need and Project Start).

- Full government funding available for the ATW project each year from 10/01/2000 to 10/01/2026 (FY 2027).

- Full funding and staff available for DOE and NRC and their ability to meet these schedule milestones during the Government-Supported Phase.

- Full funding available during Privatization Phase.

- NRC licensing of all facilities is required during all phases of the ATW project (design, construction, startup, operation for 60 years, and decommissioning).

- Public acceptance of all phases of the project and the use of all technologies.

- Public Utility Commission, FERC, and utility and labor union acceptance of plants at intended locations.

- Safeguard acceptability of project, including IAEA.

- Economic acceptability of the ATW Program as a system to improve the waste form of HLW.

- Radiation exposure acceptability.

- Ability of shops to meet component fabrication, plant module fabrication, and delivery schedules.

- Successful operation of all components systems and structures at all stages of the program.

- Ability of the national laboratories to provide follow-up data on schedule and within budget to the design, procurement, licensing, startup, and operation of the facilities.

- Ability of the contractors to meet all milestones and stay within budget.

- Ability to obtain EIS approval and permit approval on schedule.

- Extensive use of modular design for all facilities, with use of off-site and on-site fabrication shops.

- Operation of plants at each stage provides confirmatory data to the next stage. No major surprises requiring significant design and construction changes.

D.5 Critical Paths

The following critical paths are noted:

- Start of work on 10/01/1999 and approval of Mission (CD-1) on 10/01/2000 (funding restrictions).
- R&D from 10/01/1999 to 10/01/2007 to reach critical decision and provide firm data to start of Title II design and procurement.
- Completion of PEIS 42 months after 10/01/1999 and site selection on 03/01/2003.
- Obtaining all permits by 10/01/2010.
- Procurement schedules to provide detailed component information to Title II design and to deliver components to the field on schedule.
- NRC approval of PSAR and FSAR on dates shown.
- Construction, startup, and operation of facilities to meet NRC Standard Plant Certification in 10/01/2027.
- NRC issue Standard Plant Certification (10/01/2027).
- Start of Privatization in 2028, based on successful bid and award period. Start of government/privatized joint effort in 2023.

D.6 Schedule Credibility/Risk

It is important to note that the ATW schedules presented in this roadmap are based on careful reviews of schedules considered acceptable by DOE on several recent large government programs (APT, ALMR, MHTGR). Key activities, duration, and milestones for the ATW schedule closely parallel these other programs.

Comparison of schedule durations with other projects is provided in Table D.1. The reference baseline technology for the ATW program is based on relatively mature levels of development for the accelerator, a sodium-cooled burner, the IFR fuel, and the IFR pyroprocess. The ALMR licensing process is also relatively mature, based on that project receiving a satisfactory Preliminary Safety Evaluation Report (PSER) from NRC in 1994. The APT, ALMR, and MHTGR projects all had satisfactory Independent Cost Evaluations (ICE), and the ALMR had extensive schedule and cost reviews by the utilities who participated on the program with the intent of ultimately building and operating these plants. All these projects had extensive contractor participation in the design, schedule, and cost activities. These factors contribute significantly to the credibility of the ATW schedule and to the

Table D.1. Comparison of Major Activities for First Units (Duration in Months)

Project Start	ATW (10/2000)	APT (02/1996)	ALMR (10/1989)	MHTGR (10/1989)
PEIS	50	(1)	48	(1)
FEIS	16	16	15	15
Permits (construction/DP)	84	102	70	72
PSAR	60	80	60	70
Conceptual Design (2)	42	14	60	36
Title I	36	63	24	42
Title II	60	24	66	36
Procure	84	78	84	60
Construction	84	120	60	48
First Operation (Startup)	**DEMO (Small Target, Full Scale, Transmuter)**	**Complete Unit (Full Scale)**	**Prototype (Full Scale)**	**First of 4 Reactors (Full Scale)**
Date	10/2015	01/2011	03/2004	02/2002
Total Time (project start to startup)	15 years	15 years	15 years	13 years

(1) Before project start.
(2) All projects have extended conceptual design phase before project start.

moderate level of risk associated with achieving the milestones. The moderate risk favorably influences the risk level of the life-cycle cost estimate, adding to its credibility.

D.7 Government-Supported Phase

D.7.1 R&D Phase (2000 to 2008)

The R&D work for this phase of the schedule is critical to the successful demonstration of the safe and efficient operation of all aspects of the ATW program. The R&D work will be performed along parallel paths until reaching several critical decision points on 2008 relative to the selection of the coolant for the transmuter, the selection of the target, and the selection of the method for processing the LWR spent nuclear fuel. A baseline reference technology has been chosen for this ATW roadmapping report on the basis that it appears to have a high potential for success. This technology uses sodium as the coolant based on 40 years of U.S. and international experience, with several reactors built and operated. It also uses solid tungsten spallation targets based on work performed on the APT program and uses aqueous processing of the LWR spent nuclear fuel based on 30 years of U.S. and international programs, with several plants built and operated. While much work has been done on these technologies, additional R&D is needed in selected areas. The ATW schedule provided in this report is based on the reference baseline technology.

Preferred alternates to be evaluated include the use of lead bismuth eutectic (LBE) as a coolant. There is no U.S. experience on this material, but there are 30 years of proprietary Russian experience,

with several reactors built and operated. The extent to which technology transfer can be achieved to the level needed to obtain NRC licensing in the U.S. needs to be evaluated. Another preferred alternative to be evaluated is the use of an LBE target, for which no data is currently available. For the processing of LWR spent nuclear fuel, the use of pyroprocessing will be pursued as part of an on-going U.S. R&D program. It is noted that the pyroprocess for this application has the potential to be used if the need to produce a high-purity uranium waste could be relaxed, resulting in disposal in a repository other than a low-level waste site. This alternative will be evaluated.

Other alternative technologies to be evaluated include helium coolant, possibly in conjunction with an LBE target. Work performed on the recent NP-MHTGR program, the helium-cooled breeder program, the helium-cooled Pu Disposition program (in conjunction with Russian work), and international helium-cooled programs could provide a viable system. These approaches would be particularly interesting if the system uses metallic fuel similar to the sodium-cooled system and processes this fuel with the pyroprocess technology currently underway in the U.S.

In parallel with R&D work on the above alternatives, further R&D work will be performed on the baseline technology for which no preferred alternative has been identified at this time, including the use of a metallic fuel form (based on the IFR program), the ATW fuel processing (based on the IFR pyroprocess program), and the linac accelerator (based on the APT program). These reference baseline technologies, plus those noted earlier, are the basis for the site EIS, the site permitting work, the conceptual and preliminary designs of the ATW Demonstration Plant and the ATW FTF. The schedules are based on these technologies.

If the reference baseline technology changes by 2008, the work noted above will need to be revised, with subsequent changes to the schedule.

The R&D work up to 2008 will provide critical design data for the start of Title II (detailed design) of the ATW Demonstration Plant and subsequent plants, as well as for the start of the Title II for the ATW FTF.

The R&D work will largely be performed at the U.S. national laboratories, where there is currently in-depth expertise on the key technologies. This work will be coordinated by the ATW Project Office as described in Section D.7.4. The integration of the R&D work is discussed in the Systems Integration Technical Working Group report and is supported by detailed R&D discussions in other Technical Working Group reports.

D.7.2 R&D Follow-Up Phase (2008 to 2027)

Following the key decisions in 2008, additional R&D will be needed if technologies other than the reference baseline technologies are selected. The impact of selecting alternative technologies, however, has not been scheduled or cost-estimated at this time. While some pilot plant work will be done in modified existing facilities at national laboratories or other government sites, considerable pilot plant work will be done on the reference baseline technology in such facilities after the 2008 decision date. This is particularly true of the pilot plant work to be done on the fuel processing and fuel fabrication,

wherein the fuel supply for the Demonstration Transmuter's 30-MWt operation will be from the pilot plants until 2018 when the FTF begins production. Target pilot plants will supply targets to the 30-MWt and 420-MWt demonstrations until the 2018 startup of the FTF.

After the reference baseline technology is selected on 2008, considerable support will be needed from the national laboratories during the detailed design (Title II) of the ATW Demonstration Power Block, and detailed design (Title II) of the ATW FTF. These activities include support for the preparation of the PSAR and FSAR and involvement in licensing reviews with NRC, support for detailed engineering calculations of critical systems, for preparation of operation and maintenance sections of System Design Descriptions, and for preparation of technical input for procurement specification on key components. Support will also be needed during shop inspections and tests of fabricated components, and during installations, testing, startup, and early operation of key components and systems. Support will also be required during Title I and Title II design, preparation of the PSAR and FSAR, and during licensing reviews with NRC on the Standard Plant. This support will be completed at the end of the Development Phase of the project and the NRC Standard Plant Certification in 2027.

D.7.3 Demonstration Phase

D.7.3.1 Critical Decisions

The ATW project will be controlled by DOE through the use of DOE Order 430.1A, Life-Cycle Asset Management, and the associated Good Practices Guides. These will apply throughout the Government-Supported Phase of the project to its completion (2027). Major milestones within this system are:

Critical Decision One (CD-1) – Approval of Mission Need
Critical Decision Two (CD-2) – Approval of Baseline
Critical Decision Three (CD-3) – Start Build
Critical Decision Four (CD-4) – Completion/Acceptance.

For construction projects such as ATW:

CD-1 is needed to start Conceptual Design
CD-2 is needed to start Title II
CD-3 is needed to start Construction
CD-4 is needed to load fuel and start operations.

The Government-Supported Phase schedule shown in Figure D.5 identifies the following dates for the critical decisions for the Demonstration Plant.

CD-1 10/01/2000 This will cover the start of all work to be performed on the Government-Supported Phase of the project (R&D, R&D Follow-Up, and Demonstration Phase). This date is contingent on the ability to prepare a Mission Statement and Mission Justification between 10/1/1999 and 10/1/2000.

CD-2 03/01/2007 Start Title II Demonstration Plant
CD-3 10/01/2010 Start Constructing Demonstration Plant
CD-4 10/01/2015 Start Fuel Load/Startup Demonstration Plant.

For the Second Transmuter, CD-1 and CD-2 from the Demonstration Plant will be applicable, with revisions to CD-3 and CD-4 as noted:

CD-3A 10/01/2019 Start Construction of Second Transmuter
CD-4A 10/01/2022 Start Fuel Load/Startup Prototype Plant.

For the Standard Plant Design and Licensing effort, the CD-2A on 10/01/2017 will initiate the start of Title II.

For the FTF, CD-1 will be the same as discussed above, with new dates for CD-2, CD-3, and CD-4 as follows:

CD-2B Start Title II FTF
CD-3B Start Construction FTF
CD-4B Start Operation FTF.

D.7.3.2 Environmental Impact Statements

A Programmatic Environmental Impact Statement (PEIS) will be needed for the ATW Program. The PEIS that was prepared for the High-Level Waste Repository Program in 1989 will be revised to reflect the Government-Supported Phase of the ATW Program and will discuss the deployment of the FOAK plants and NOAK plants, fuel transportation, power generation, and other aspects. Based on using material from the current HLW PEIS, the total duration for the ATW PEIS is 43 months. This includes the following steps as provided by the NEPA guidelines:

- Preparation of EIS management plans and public participation plans
- Preparation of RFP/award contract
- Issue Notice of Intent (NOI)
- Conduct Public Scoping Meetings and prepare result documents
- Provide description of alternatives
- Issue draft PEIS for public review
- Public review draft PEIS
- Issue Final PEIS
- Issue Record of Decision (ROD).

The ROD is scheduled to be issued 03/01/2003, based on a 10/01/1999 start for this effort. Based on the ROD, the site can be selected for the Development Phase of this program.

Following site selection, the specific facility/site EIS can be prepared in about 22 months, based on the same NEPA guidance steps defined for the PEIS. This EIS will cover the operation of all government and privatized FOAK facilities on the first government site.

D.7.3.3 Permits

State and local construction and operating permits are required for all the facilities to be built on the first government site. This includes permits to construct and operate all the ATW accelerator/transmuter facilities and all the FOAK plants, including Fuel and Target Facilities. Using the APT project as a recent example of scope and schedule, as well as the ALMR project with its six sodium-cooled reactor modules and on-site fuel process facility, a seven-year duration for all permitting has been shown on the schedule. The permits require plant design data input (including air, water, solid, and release data) early in the design of the plant. All construction permits must be issued before construction. All operating permits must be issued prior to operation.

This schedule assumes that radioactivity releases from the ATW plant can be kept below the 0.1 mrem/yr level at the boundary of the ATW plant site to avoid the need for a NESHAP review and permit (which could require up to 3 years). Calculations to confirm that the plant design can accommodate these limits will be continually updated. Other air and water permits, and RCRA permits, are included in the 7-year duration.

D.7.3.4 NRC Licensing

NRC licensing is assumed to be required, consistent with current government planning for future large nuclear projects. This licensing will include the ATW transmuter and all associated systems and components for the Demonstration Power Block, and all subsequent power blocks. The extent to which NRC licensing will be required for the accelerator in this application has not been determined at this time. NRC licensing will also be required for the FTF. PSARs and FSARs will be needed for each facility.

A major milestone in this schedule will be to obtain an NRC Standard Plant Design Certification for the second generation power blocks and for the next FTF. This certification will be the basis for the privatization of those blocks to begin in 2028. This certification is not needed for constructing Power Blocks 2, 3, and 4, but it does provide additional assurance to the privatization of these units.

Each new station at a new site will require separate PSAR and FSAR updates, but the NRC Standard Plant Certification will provide good assurance of a successful, brief licensing effort.

D.7.3.5 Demonstration Transmuter

The schedule (Figure D.5) provides adequate durations for the conceptual design, Title I, and Title II efforts, based on other similarly complex projects. Procurement and fabrication durations are achievable, and permit the accelerator to be constructed to permit a 2-year startup duration prior to the startup of the 30-MWt Demonstration Plant burner in 2015. A Limited Work Authorization (LWA) will be received on 2009, 2 years before CD-3 (Start Build) to permit excavation and other site work. The construction

duration of 5 years (following the 2 years of work under the LWA) is sufficient, and is based on extensive use of shop-fabricated equipment and plant section modules. Off-site and on-site fabrication shops will be used.

Startup of the Demonstration Transmuter in 2015, with operation at 30 MWt and increased in incremental steps to 450 MWt, will provide confirmation of the safe and efficient operation of the system. The operating data will be used to finalize the design of the second transmuter. In 2022, the DHX is removed from the Demonstration Transmuter and replaced with the steam generator and turbine generator system as the heat sink. With the addition of the turbine generator system, the Demonstration Transmuter power level will be increased to 840 MWt. An FSAR update will be required prior to the start of operation at the full-power level.

A Startup Test Report will be submitted to NRC as the final input to the process of obtaining an NRC Standard Plant Certification. Full power operations will begin on 2023, with 4 years of power operation to be observed by NRC before issuing the NRC Standard Plant Certification by the end of 2027.

D.7.3.6 NRC Standard Plant Design and Licensing

The design organization will prepare licensing drawings, specifications, system design descriptions, etc., during the Standard Plant Title I and Title II design period (for an eight-transmuter standard plant) as shown in Figure D.5. The safety assessments for the Standard Plant will be completed for submittal to NRC at the end of the Title I period. The configuration of the Standard Plant will be as shown in Figure D.3. The Title I and Title II design effort will be based on the design work done for the Demonstration Power Block, and will reflect construction and operating experience from those plants. The final submittal of licensing documentation will occur at the end of Title II. NRC final review will occur from 2023 to 2027, with licensing support from the design organization as required. A satisfactory startup report from the full-power Demonstration Transmuter in 2023 will be a key input to the certification process.

The NRC Standard Plant Certification will also include the FTF and will be based on the Title I and Title II design efforts performed for the FTF between 2005 and 2012. Construction and operating experience from the FTF will be submitted to NRC on 2023 for the NRC final review.

NRC Standard Plant Certification permits the privatization of the power blocks, starting in 2028.

D.7.3.7 Fuel and Target Facility

The design, procurement, licensing and construction of the FTF will proceed on an independent path from the ATW power block path. They will share the same site, and the EIS and site permits will apply to all facilities on the site.

Design data from the R&D Phase of the project, with decisions on processing by 2008, are essential to meeting the schedule shown in Figure D.5. Separate NRC safety reviews of the PSAR and FSAR are required, and separate DOE approvals are needed for CD-2, CD-3, and CD-4.

The 7-year duration of Title I and Title II is reasonable, based on the schedules for other facilities. A 5-year procurement duration provides for delivery to the site of equipment needed for processing fuel in the early years, with delivery of the remaining equipment to extend an additional 5 years if required. The equipment and systems will be full-size (on extrapolation from the pilot plant equipment), with some systems operated at reduced capacity as ATW plants come on-line.

D.7.4 ATW Project Office

The schedule is based on the presence of an ATW Project Office to coordinate all aspects of the program from the start of the project to the completion of the Government-Supported Phase (2027). This includes integration of the work performed by each of the national laboratories during the R&D and R&D Follow-Up Phases of the project. This also includes managing the interfaces between the laboratories and the contractors responsible for the design, licensing, procurement, and construction of all facilities on the first government site (Figure D.5).

The ATW Project Office will be responsible for the preparation of all project level and plant level documents, procedures, reports, etc., with input from the national laboratories and contractors. These activities include the overall responsibility for the preparation of the PSAR and FSAR, site permits, overall plant design descriptions, engineering cost estimates, plant capital cost estimates, schedules, QA programs, and for design reviews and readiness reviews throughout the project.

The ATW Project Office will monitor the progress of the national laboratories and the contractors with an approved cost and schedule reporting system, and will report the status of the project monthly to DOE. Each national laboratory and each major contractor will be responsible for the performance of their own work (technical, cost, and schedule) and will provide input to support the work of the ATW Project Office.

The ATW Project Office will start to be formed on 10/01/1999, with a few people concentrating on the preparation of the Mission Statement and Mission Justification to obtain a CD-1 (Approval of Mission Need) by 10/01/2000. Some work also needs to begin on the PEIS process. Early staffing by a few people to perform scoping efforts can be from national laboratories, contractors from the APT Project, and other contractors as available on a limited consulting basis. Bid documents should be prepared to award contracts after CD-1.

Contractual arrangements between DOE, national laboratories, and contractors, and between these organizations and subcontractors will require development early in the project so that an RFP can be issued shortly after the CD-1 approval.

Appendix E

Accelerator Development and Deployment Costs

Appendix E

Accelerator Development and Deployment Costs

The ATW accelerator cost estimate is based upon the Accelerator Production of Tritium (APT) project cost estimate (ref: TPO-P00-G-TS-00014, Rev O, "*Modular Design Study, Phases I & II*", March 1999). The APT project currently uses a hybrid normal conducting/superconducting architecture to deliver a 1030-MeV, 100-mA CW proton beam. This linac configuration contains all the same accelerating structures that ATW employs, over similar acceleration ranges. Further, the APT cost estimate is the result of over 10 years of concerted effort that includes a full-time effort from an industrial partner, Burns & Roe Enterprises Inc. and General Atomics, since 1996. During this time the APT project has successfully defended the cost estimates in a series of independent cost reviews (two independent Cost Estimate Reviews in 1997, and three independent cost audits dictated by the DOE–one performed by the Government Accounting Office). This firm foundation provides the basis for the ATW estimates listed in detail below.

E.1 Summary

The estimated base costs for design, construction, upgrading, operations and maintenance (O&M), and decontamination and decommissioning (D&D) are summarized in Table E.1. The design costs for the first accelerator include conceptual, preliminary, and final design, and the preparation of appropriate documentation such as design and operations manuals, etc. Construction costs include direct construction costs, spare equipment, and construction management. Operations costs include staff labor, repairs and refurbishment, and electric power for the first accelerator until the unit is upgraded and the first transmuter w/turbine-generator system is service. Thereafter, the electric power is provided by the on-site generation capacity. After about 7 years of operation at a nominal 12-mA beam current to develop and demonstrate the required level of reliability for ATW service, the first accelerator is upgraded to provide a nominal 45-mA beam current for full-power operation of the first and subsequent transmuter units on the site. Decommissioning of the accelerators is estimated to cost about 5% of the initial construction cost of each unit, in the same year's dollars.

Table E.1. Estimated Base Costs for Elements of the Accelerator System (millions of 1999 dollars)

Cost Element	First Accelerator	Second Accelerator	3RD and Subsequent Units
Design	425	164	164
Construction	1251	1079	1079
Upgrade	60	--	--
O&M	61 @12 mA	44 @45 mA	44 @ 45 mA
D&D	63	54	54

The rapid-deployment scenario used in the costing approach is to develop a demonstration plant where ATW technologies can be evaluated prior to building a full-scale production ATW facility. The Demonstration linac will be built to 1 GeV and 11.25 mA in the first phase, which matches the requirements of the first transmuter unit. The Demonstration linac will be designed and built with the intent to eventually upgrade to a full power production linac (45 mA). In the initial phase, all necessary space for rf power generation, transport, and insertion will be fabricated and installed. The essence of the upgrade to 45 mA will be to install new rf power stations (dc power supplies, klystrons, drivers, and transport sections) making the mechanical connection to pre-existing drive points on the linac structure and facility services feeds. This approach delivers a slightly more expensive Demonstration linac than one optimized for operation at 11.25mA, but enables considerable schedule savings during the upgrade phase of the project. After the Demonstration linac has operated at full power (45 mA), and all development tests have been completed, the Demonstration facility is devoted to full-time transmutation activities, the first of the two production accelerators required for the first production ATW facility.

Lessons learned in the fabrication, installation, operation, and upgrade of the Demonstration facility will be incorporated in the design of the second production accelerator. The accelerators for subsequent stations will incorporate design improvements derived from the operating experience with the earlier units.

E.2 Linac Estimate Work Breakdown Structure and Interfaces

To maximize traceability between the reviewed and accepted APT cost estimates and evolving ATW estimate, the APT Linac Work Breakdown Structure (WBS) is used for ATW with additional scope added to cover necessary activities that the APT project book keeps in other WBS elements. These additional ATW resources are added to the last ATW WBS element, *Linac Miscellaneous Systems*. A full listing of the APT project WBS, including an associated dictionary describing the contents of each element, can be found in LA-UR-97-1329, "*Conceptual Design Report for the Accelerator Production of Tritium Project,"* dated April 15, 1997. The resulting traceability matrix between ATW and APT is shown in Figure E.1.

ATW	APT	
WBS Name	WBS Number	WBS Name
Low Energy Accelerator (injector RFQ, and CCDTL)	1.06.01	LE Accelerator (0-211MeV)
Superconducting RF (SCRF) Linac	1.06.02	Superconducting RF (SCRF) LINAC
High Energy Beam Transport (HEBT)	1.06.03	High Energy Beam Transport (HEBT)
Radio Frequency (RF) Power Systems	1.06.04	Radio Frequency (RF) Power Systems
LINAC Auxillary Systems & Cryoplant	1.06.05	LINAC Auxillary Systems
LINAC I&C Safety & Protection	1.06.06	LINAC I&C Safety & Protection
LINAC Beam Diagnostics	1.06.07	LINAC Beam Diagnostics
Modified for ATW	1.06.08	Integration with BOP
Operations, Protection, Safety	1.06.09	Operations, Protection, Safety
LINAC Miscellaneous Systems (including Buildings and Program Management)	1.06.10	LINAC Miscellaneous Systems

Figure E.1. Traceability Matrix Between ATW and APT

The first WBS element, Low Energy Accelerator includes the injector, 6.7 MeV radio frequency quadrupole (RFQ), and Coupled Cavity Drift Tube Linac accelerating elements. This section of the accelerator brings the beam to the transition energy necessary to enter the superconducting accelerating section.

The Superconducting rf (SCRF) Linac section contains five different sections of superconducting linac. Each section is designed for a specific acceleration range with the cavity type and design optimized for use across a specific energy range. These cryomodules are based around both spoke resonator (Sections 1,2, and 3) and elliptical accelerating cavities (Sections 4 and 5). Interfaces for this element include the cryogen distribution system at the feeds on the external surface of the cryomodule with the rf power delivered to the windows installed on the cryomodule during fabrication. As such, the window and antenna are part of the cryomodule assembly. Last, unlike the APT, the ATW design utilizes superconducting singlet magnets between cavities inside the cryomodule for focusing.

The High Energy Beam Transport (HEBT) WBS element contains the necessary transport elements (magnets, beam pipe, diagnostics, vacuum systems) to deliver the beam from the output of the linac to each transmutation burner assembly. In the demonstration implementation, the HEBT element also includes a full energy beam-stop assembly used in commissioning activities.

The rf power system WBS includes all the necessary components to connect to the balance of plant electrical feeds to the site starting at the step-down transformers (included as part of the rf power system) through the high voltage dc power supplies, the main amplifiers, and rf transport components.

The Linac Auxiliary Systems WBS contains the thermal control, vacuum, and cryogenic supply and distribution subsystems of the linac. They supply the necessary cooling water and vacuum to the rf power system, linac structures, and cryoplant to ensure proper operation of the components. Major interfaces with the balance of plant are for the thermal control system with a variety of water flow rates and types at distributed headers on the wall of each major linac structure. Similarly, electrical power will be required throughout the facility to run associated power supplies and pumps attributed to the linac balance of plant. The APT component fabrication and installation charges were kept unchanged for ATW cryogenic plant and vacuum subsystems. Last, this element contains the ~7 kW 1.8K helium supply and distribution system that requires the balance of plant to supply electrical power directly to the cryoplant.

As the name implies, the Linac Instrumentation and Control, Safety, and Protection WBS element contains the necessary resources to provide the components and software to safely operate the linac system components. Further, this WBS contains the necessary safety enable-and-fast-protect systems that guard both linac operations staff and the accelerating components from damage.

The Beam Diagnostics WBS element provides specialized instrumentation to understand the instantaneous operation of the linac systems. This information is used to optimize the overall operation of the linac systems, as well as to predict impeding component failure and to understand the impact of any unexpected component failures.

The Linac Miscellaneous Systems WBS contains the necessary specialty shops and support facilities required by the linac systems during component fabrication, system startup, commissioning, and long-term operation. The specific shop capabilities included in this WBS are

- rf Test Stand
- Cryomodule Test Stand and Clean Room
- HV PS Maintenance Shop
- LLRF Maintenance Shop
- rf Structures Lab
- Alignment Lab
- Electronics and diagnostics Lab
- Vacuum Support Shop
- Magnet Maintenance Shop
- General Purpose Machine Shop with Brazing Capability.

Furthermore, this WBS contains the specific scope that must be added to the APT elements for ATW. These additional elements fall into three separate categories. Specifically these are: 1) buildings and enclosures, 2) system engineering and, 3) project management. The building and enclosure additional scope includes all the necessary design and "brick and mortar" resources to cover the injector building, linac tunnel, rf hall, interconnecting tunnels for rf transport, cryoplant building, interconnecting trenches and tunnels for cryogen distribution, and an enclosure for the specialty shops (maintenance, rf measurement, magnet lab, optics lab) required to support both linac installation and ongoing maintenance. Interfaces for site services are assumed to be at the building perimeter with all internal distribution included in the linac accounts.

Additional resources were added to cover system engineering provided for linac system preconceptual design and ongoing support of the larger centralized facility safety and licensing activity.

Last, additional resources were added to reflect the required linac specific project management, as well as interfacing the linac effort with the balance of the ATW project activities.

E.3 Modifications to APT Estimate to Develop an ATW Linac Estimate

Individual APT estimates are composed of three major costs: Preliminary and Final Design (P&FD), Component Fabrication, and Installation and Checkout. In each of these categories, the APT project developed relationships between the number of any component and the final cost estimates. In most instances the APT relations were used for ATW with minor modification to account for results or developments from the APT project Engineering Design and Development (ED&D) activities.

Injector: The APT P&FD estimate was reduced to reflect the APT and ATW injector development activities.

RFQ: The APT P&FD estimate was reduced to reflect the existence of the LEDA RFQ design packages. Furthermore LEDA actual cost estimates for the component fabrication and installation activities were used for ATW.

CCDTL: The APT P&FD activities for the CCDTL section were reduced to reflect the greatly reduced number of tanks in ATW. Component fabrication and installation estimates were adjusted to reflect the quantity of CCDTL tanks required by ATW.

Superconducting Linac (SCL) Sections 1 – 5: One of the major thrusts of the ATW R&D activities is to develop cryomodule designs and functional prototypes for both a spoke resonator and elliptical accelerating cell cavity configurations. Further, the ATW development effort will also produce superconducting singlets for incorporation in the developmental cryomodules. These results combined with the expected successful results on similar APT cryomodule component development tests lead to a reduction in the P&FD costs associated with the ATW cryomodule design. However, where APT had only two basic cryomodule configurations, ATW currently uses five separate configurations. Each configuration requires a certain level of non-recurring design activity associated with the preparation of drawings and procurement specifications. Once the non-recurring engineering is complete, the recurring component of design cost was considered. Since ATW employs higher accelerating gradients than APT, the ATW configuration requires a lower number of total accelerating cells. The lower number of accelerating cells, coupled to eight cell cavities delivers more efficient acceleration per meter. APT component fabrication and installation costs, and their relationship to component count, were used directly in the compilation of the ATW cost SCL estimate. Earlier APT estimates for superconducting singlet magnets were applied in favor of adjusting the existing APT room temperature doublet estimates.

rf Power Systems: The APT configuration employs both 1.2-MW 350-MHz and 1.0-MW 700-MHz power stations whose costs are directly applicable to the ATW Demonstration plant. In the initial deployment (11.25 mA), the power system costs include additional charges for rf hall preparations for the upgrade stations. The remaining costs for the upgrade include the component purchase and installation of the additional rf stations in the rf hall. No separate installation labor is required for the upgrade. Since the linac operations are suspended, the operations staff will be used to support the upgrade activities.

Beam Diagnostics and Instrumentation and Control, Safety, and Protection: Since ATW has not begun detailed analysis of the Beam Diagnostics or Instrumentation and Control architecture, the APT estimates were used unmodified.

High Energy Beam Transport (HEBT): Since ATW has not begun detailed analysis of the HEBT architecture, the APT estimates were used unmodified. This approach assumes successful development during the R&D phase of low loss superconducting beam splitters.

Linac Auxiliary Systems: The APT estimate basic cost relationships for the P&FD, component, installation, and checkout costs were used with the ATW requirements.

Linac Miscellaneous Systems: The APT estimates for the P&FD of the support shops included in this WBS element were used unchanged for ATW. Similarly, the component cost relationships associated

with each shop size were employed for ATW. Since ATW uses a different number of rf stations and cryomodules, the costs associated with these maintenance plants were adjusted accordingly. To arrive at appropriate building and enclosure costs, the basic APT relationships ($k/meter or $M/meter^3) were applied to the ATW requirements. Similarly, the APT project management costs were adjusted to meet the size of the ATW effort.

E.4 Production Station Estimate (Two 1-GeV, 45-mA Linacs)

Design: Successful operation of the Demonstration plant will provide valuable information enabling significant improvements in the design of the first production plant estimate. Since these improvements will be targeted at only key subsystems of the linac, they are expected to require only minimal resources. Similarly, each subsequent plant would be able to access a rapidly expanding database of design and operation information. The design costs associated with the first (demonstration) accelerator are estimated to be $425 million, and for the second accelerator, $164 million. The design costs for the accelerators on Station 2 and subsequent stations are reduced from the second accelerator by a factor of 0.15 and by using 95% learning curve factors.

Component Fabrication, Installation, and Checkout: The Demonstration plant is truly the first-of-a-kind (FOAK) and its estimated construction cost ($1251 million) reflects the somewhat experimental character of that unit in its initial operations. The cost to upgrade the initial demonstration accelerator to full power operation is estimated to cost an additional $60 million. The second accelerator is the first of N-of-a-kind (NOAK), with its estimated construction cost of $1079 million, reduced from the first accelerator cost to reflect lessons learned during the construction and operation of the first unit. Subsequent accelerator unit construction costs are adjusted using 85% learning curve factors.

E.5 Operations Cost Estimate

The operations and maintenance estimate for ATW is based upon the APT methodology that considers three separate elements: 1) electric usage, 2) operations staff, 3) linac and facility component repair and refurbishment.

Electric usage was calculated using $0.06/kWe-hr and operation for 70% of a calendar year, and applies only to the first accelerator prior to its upgrade. Subsequent use of the first accelerator and all other linac deployments will be on stations with power generating transmuter/turbine-generator systems that supply power for the linacs. Therefore, no further direct charge for electricity is required. To estimate the operational staff required, APT projections were combined with operational experience on the Los Alamos Neutron Science Center (LANSCE). To support 24-hour operation, a complete staff of 220 full-time equivalents (FTE) is assumed to be required for the first accelerator, with a fully burdened labor rate of $110 k/year. Subsequent units are assumed to require an operating staff of 165 FTEs, reflecting the transition from an R&D type of staffing to a production operations type of staffing, and the sharing of some staff with the companion unit on the site. Component and facility repair and refurbishment were estimated at ~$25M/year for each unit.

E.6 Contingency

The APT estimate has received a concerted effort to capture and express the inherent uncertainty of the overall estimation process (technical risk, individual cost estimate uncertainty, and schedule risk) and has arrived at a global contingency factor of about 23% for the linac systems. The APT work breakdown structures were examined carefully to ensure that only the appropriate costs were translated into the ATW cost estimate. A number of APT system elements were deleted from the APT cost, e.g., the target building and the tritium processing facilities, etc. The balance of plant functions from APT were reduced for ATW because many of those functions at ATW would be provided by the Station site support function.

The components of the estimated costs for the first and second accelerator are shown in Table E.2, together with the corresponding estimated costs from the APT program, from which the ATW costs were derived. The contingencies assigned to the individual components of the ATW estimate are also derived from ATP program documents and were used to arrive at the total ATW estimated costs.

Table E.2. Estimated Costs for Initial Accelerators
(millions of 1999 dollars)

	ATW Accelerator No. 1			
Design	**APT Estimate**	**ATW Estimate**	**Contingency (%)**	**Total Cost**
Conceptual	20	20	0	20
Prelim & Final	219	163	15	187.45
ES&H, S&S	58	60	25	75
Startup	220	100	15	115
Proj. Mgmt.	26	26	7	27.82
Totals	543	369		425.27
Construction				
Linac	605	479	25	598.75
PSB/BOP	518	352	25	440
Const. Mgmt.	160	160	15	184
Spares	26	26	10	28.6
Totals	1309	1017		1251.35

	ATW Accelerator No. 2 (NOAK)		
Design	**ATW Estimate**	**Contingency (%)**	**Total Cost**
Conceptual	0	0	0
Prelim & Final	40	15	46
ES&H, S&S	0	0	0
Startup	100	15	115
Proj. Mgmt.	3	7	3.21
Totals	143		164.21
Construction			
Linac	436	25	545
PSB/BOP	276	25	345
Const. Mgmt.	140	15	161
Spares	26	7	27.82
Totals	878		1078.82

Appendix F

Transmuter/Power Facility Cost Basis

Appendix F

Transmuter/Power Facility Cost Basis

F.1 Description of Transmuter/Power Facility Cost Basis

For the purpose of developing a life-cycle cost estimate for the ATW roadmap, it was determined that the U.S. Advanced Liquid Metal Reactor (ALMR) would provide a reasonable cost basis for the Transmuter/Power Facility. The ALMR was a DOE-funded program from 1989 to 1995 and reflected more than 30 years of U.S. and international design and operation of sodium-cooled fast reactors. This maturity of the technology provides for a highly valid cost estimate for the ALMR. The ALMR design received a satisfactory NRC review of the Preliminary Safety Evaluation Report in 1993. Designs and costs were extensively reviewed by ORNL and by independent utility (user) review teams. Commercial deployment potential was considered to be excellent. No other Transmuter/Power Facility design and cost estimate was available for the ATW roadmap that had a comparable level of information.

Lead bismuth eutectic (LBE) has been identified as the preferred technology for the ATW coolant. However, because we do not have sufficient information on LBE Transmuter/Power Facilities, the sodium coolant was selected as the reference basis for the ATW roadmap. The overall costs for the sodium and LBE coolant may be similar, since the basic components and systems for these two liquid metal systems are expected to be similar but with some size differences associated with coolant efficiency and spallation target and neutronic efficiency. Future studies and R&D will determine the final outcome. Other possible coolants, such as helium, may have considerably different cost estimates.

The ALMR requires modifications to make it suitable for use as the ATW Transmuter/Power Facility. These modifications are mainly associated with the reactor vessel (RV) and its internals, the RV head, refueling systems, control rod drive systems, in-vessel and ex-vessel fuel handling systems, component removal systems, sodium cleanup systems, cover gas systems, instrumentation, and control. Considerable modifications are also needed for the containment building to accommodate the accelerator beam tube and its supports, and space for the refueling equipment and other casks and cranes above the RV head. Accommodation of the radiation shine pathway from inside the RV to the containment building is a significant design challenge. These modifications will impact the ALMR cost estimates. No significant changes to the ALMR cost estimate beyond the containment building modifications are expected. The ALMR costs were used for the intermediate heat transport system, steam-generator system, turbine-generator system, heat removal system, electrical distribution systems, and all other balance of plant (BOP) systems.

The configuration of the ALMR was three power blocks, each providing 620 MWe with one turbine generator connected to two 840-MWt reactors. Total power was 1860 MWe at one site. The configuration of the ATW Transmuter/Power Facility is four power blocks of 620 MWe each to produce a

total of 2480 MWe at one site. The cost estimate for ATW reflects this change in terms of capital and operating costs. Changes in the refueling cycle from once every 18 months in the ALMR to once every 6 months in the ATW, plus the need for target replacement in the ATW, increases the equipment and operating costs for the ATW. The instrumentation and control (I&C) costs for the ALMR will be increased to reflect the interfaces with the accelerator I&C systems in a fully integrated control building. Most of the above considerations will also apply to the design of an LBE coolant Transmuter/Power Facility.

F.2 ALMR Modifications for ATW

The anticipated modifications to the ALMR facilities to accommodate the ATW mission are described in the following subsections.

F.2.1 Reactor Vessel

The use of the ALMR RV as the subcritical reactor for the ATW Transmuter/ Power Facility was only selected as a basis for a roadmap cost estimate and was not evaluated to any appreciable degree. This evaluation will be done as part of the R&D program. Some initial considerations on this potential new use of the ALMR RV are as follows:

- A new ATW core, ATW target assembly, and a beam tube will require major design efforts. It is assumed that the 31-ft diameter, 64-ft long ALMR RV will have sufficient space to provide for these features. The primary electro-magnetic (EM) pumps, intermediate heat exchangers (IHX), the decay heat removal heat exchangers, the in-vessel fuel handling equipment, and other features should not require major modification.

- The vertical beam tube through the RV head will probably have to be removed during in-vessel refueling, requiring many special design considerations.

- The radiation shine path from inside the RV to above the RV head is an unresolved issue. Space and weight of shielding are key considerations.

- The presence of the beam tube in the space above the RV head presents potential interference with the polar crane, transfer casks for pump and heat exchanger removal, and refueling machine, with added costs needed for seismic support of the beam tube and its magnets and shielding.

- Manned access to containment during operation may be prevented, requiring changes to the design of equipment in this area, including relocating some EI&C cabinets outside of containment.

- The RV is seismically supported and will move horizontally (and vertically) during an earthquake. Connections to the beam tube must be considered, as well as rapid beam shutoff. Beam stops will be required outside containment (part of accelerator BOP cost estimate).

- High-energy protons and neutrons scattering inside the RV may require some design change to components and structures.

- Target removal equipment must be provided.

F.2.2 Auxiliary Nuclear Island Systems

The following ALMR systems may be impacted by the ATW application.

- Sodium cleanup system (cold traps, hot traps) will need to handle spallation products (either in primary coolant or in a separate target assembly loop).

- Cover gas system may require redesign to accommodate frequent refueling, bean tube removal, and target removal.

- Control rod drive systems should be simpler (few control rods).

- Instrumentation may be similar in the RV, but overall instrumentation and control system for plant will be more complex.

- Refueling equipment used to remove fuel from the reactor vessel and to transfer it to the fuel storage pool at the ATW Processing Facility will have a greater duty cycle for ATW, due to the need to refuel each transmuter every 6 months versus every 18 months for the ALMR. An additional refueling machine has been added to the ATW cost estimate.

F.2.3 Changes to the ALMR Cost Estimates

- Addition of a fourth power block of the same size as each of the ALMR power blocks, with subsequent increase in turbine generators, heat removal, and electrical equipment, and associated buildings, piping, cable, etc.

- Increased size of control building for fourth power block and for the accelerator control room for two accelerators.

- Increased land costs for the fourth power block and fuel cycle facilities.

- Additional cooling water and power for the accelerators and the fuel cycle facilities.

- No other changes were made to the ALMR construction costs.

- An additional 10% was applied to the capital costs derived from the ALMR report to allow for the increased uncertainty in the estimate arising from the additional complexity discussed above.

F.3 ALMR Cost Estimate Modifications

The ALMR Cost Estimate was modified to reflect the modifications to the nuclear island and to provide four power blocks per station, instead of three power blocks. The cost estimate for the Transmuter/Power Facility utililzes the nuclear island (NI) and BOP cost estimates defined in the ALMR 1994 capital and Busbar Cost Estimates, GEFR-00940, March 1995, which were modified for ATW as described previously. The estimated capital costs for the first, second, and subsequent ATW transmuters, the initial turbine-generator system, and the site support functions derived from the ALMR reference data is summarized in Table F.1, with the detailed analyses given in Tables F.3, F.4, and F.5, below.

Table F.1. Summary of Capital Costs Derived from ALMR Reactor Design Studies (millions of 1999 dollars)

	Single T-G Set	**Single Transmuter**	**Station Site Support[(a)]**	**Single Power Block**
FOAK(1) Single	391.6	671.8	118.1 (1)	1735.3
FOAK(3) Multiple	330.9	520.7	175.0 (4)	1372.3
NOAK(3) Multiple	301.6	430.1	163.3 (4)	1161.8
(a) Numbers in () refer to the number of power blocks supported.				

The capital costs associated with the additional complexity and equipment for modifications to the first two transmuters on Station 1 are estimated to be $67.9 million and $56.6 million, respectively, in 1999 dollars. Similarly, the complexity cost increases to the first commercial power block on Station 1 are estimated to be $76.6 million per power block, in 1999 dollars. Adding these incremental costs to the capital costs given in Table F.1 results in the values shown in Table F.2, assuming that the design and construction costs are 10% and 90% of the capital costs, respectively

Table F.2. Estimated Design and Construction Costs (millions of 1999 dollars)

	FOAK Single		**FOAK Multiple**		**NOAK Multiple**	
	Design	**Construct**	**Design**	**Construct**	**Design**	**Construct**
1 Transmuter	74.0	665.7	57.7	519.6	48.7	438.0
1 Turb.-Gen.	39.2	352.5	33.1	297.8	30.2	271.4
Site Sup. (4 PB)	17.5	157.5	17.5	157.5	16.3	147.0
1 Power Block	181.2	1630.7	144.8	1304.0	123.8	1114.6

Thus, the total capital costs for those initial units are estimated to be $739.7 million and $728.4 million in constant 1999 dollars. The total capital cost for the first commercial power block on Station 1 is estimated to be $1448.9 million 1999 dollars. Subsequent power block costs are reduced using a 95% learning curve factor.

F.4 Interfaces of the Transmuter Estimates with Other Site Facilities

The interface with the Accelerator Facility (Accelerator and Accelerator BOP) is as follows:

- The beam tubes from the two accelerators to the eight containment vessels are provided in the accelerator BOP Cost Estimate. Also included are the beam stops and splitters required in this proton delivery system. Beam tube tunnels are also provided and reflect the need to avoid conflict with the refueling system rail system to containment. Beam tubes inside containment are provided in the Transmuter/Power Facility Cost Estimate.

- The Accelerator Facility Cost Estimate includes all I&C costs for integrating the accelerators with the transmuters including the interconnecting cabling and the control room for the accelerators. The control room for the Transmuter/Power Facility is included in that cost estimate. The integrated plant control building is included in the Transmuter/Power Facilities Cost Estimate.

- The Accelerator BOP Cost Estimate includes all heat exchangers, service buildings, systems, and all other costs needed to support the accelerator, as described in the APT cost estimates (and modified to suit the ATW configuration). In the future, some sharing of BOP facilities, such as heat exchangers, service water systems, etc., can be accomplished, but since the accelerator will be operating many years before all the Transmuter/Power Facilities are constructed for the first eight burner stations, these costs were kept separate at this time.

The interface with the Separations Facility is as follows:

- The Separations Facility Cost Estimate assumes the following being supplied by the Transmuter/Power Facilities:
  -- Administration Building
  -- Security Building
  -- Water Supplies
  -- Cooling Water
  -- Electricity
  -- Road Systems
  -- Other site services.

The Separations Facility provides its own control room, warehouse and repair shops, and the fuel storage pool for the irradiated ATW fuel that is removed from the transmuters and for storage of all irradiated control rods and target assemblies.

F.5 Details of Derivation of ATW Costs from ALMR Report

Detailed breakdowns of the cost estimates made for the ALMR study are given in Tables 8.1 through 8.4 of (GE 1995a). Those estimates are used in the following tables (F.3, F.4, F.5) as the bases for developing cost estimates for individual transmuters, individual turbine-generator sets, and for the site

support functions necessary to support the operation of the transmuter power blocks. The ALMR estimates are presented in terms of the nuclear island (transmuter) and the balance of plant (which includes both the turbine-generator systems and the site support systems). Because the modeling of the ATW system in our spreadsheet required costing individual transmuters, turbine-generator sets, and whole site support services separately, it was necessary to manipulate the ALMR data to obtain those individual costs. This separation was accomplished in the following manner:

The data given in the reference tables for the transmuter and the BOP are repeated in columns 2 and 5 of the tables below. The portions of the BOP applicable to the turbine-generator system are listed in the third column. The portion of the BOP direct costs remaining after removing the turbine-generator direct costs are assigned to the Site Support function in column 6. The indirect costs for the BOP are apportioned to the turbine generator and to the site support function by the fractions of the BOP direct cost that each represents (columns 8 and 9). The base construction costs for the three elements are the sums of the direct and indirect costs. The contingency for the BOP was allocated to the T-G and Site Support in the same manner as the indirect costs. The total Over Night Costs (ONC) are the sums of the base construction costs and the contingencies. The Interest During Construction (IDC) was divided into Transmuter and BOP portions, using the fractions of total direct cost that each represents (column 7 for BOP). The BOP portion was further allocated to the turbine-generator set and to the site support function by their fractions of BOP direct cost. The total capital cost for each element is the sum of the ONC and the IDC portions. To estimate the cost of a single power block (which is composed of two transmuters and one T-G set, without the site support function), the total capital cost of the transmuters and the T-G sets are summed in column 4. The total capital costs for each part of the plant are escalated (1.1313) from 1994 $ to 1999$. The three-power block site support cost is multiplied by 4/3 to obtain the cost of a four-power block site support function, as is the design for ATW. The cost of a single turbine-generator set is obtained by dividing the result for three sets by 3. Similarly, the cost of a single transmuter is obtained by dividing the result for three power blocks (six transmuters) by six, and for a single power block by dividing the three power block result by three. The results of the analyses in Tables F.3, F.4, and F.5 are summarized in Table F.2.

Table F.3. Three Power Block FOAK Station

3 Power Block FOAK data, Table 8-2, GEFR-00940, March 1995. (Thousands of 1994 dollars)

WBS No.	BOP (3)	Turbine-Gen (3)	Power Block(3)	Transmuters(6)	Site Support (6)	BOP/Total	T-G/BOP	S.S./BOP
20	10,753							
213		28,550		-				
21	51,268			255,312				
22	-	-		981,926				
23	278,926	278,926		1,631				
24	62,011	62,011		45,482				
25	20,739			15,730				
26	40,596	40,596		-				
Direct	464,293	410,083		1,300,081	54210	0.2631	0.8832	0.1168
Indirect	230,979	204,010		460,334	26969			
Base Const.	695,279	614,093		1,760,415	81179			
Contingency	66,707	58,918		354,314	7789			
Total O.N.C.	761,981	673,012		2,114,729	88967			
IDC	141,287	124,791		395,623	16496			
Total Capital Cost	903,268	797,803		2,510,352	105464			
w/Addnl. 10% Contg.	993,595	877,583	3,638,970	2,761,387	116010			
Escalate to 1999	1,021,867	992,809	4,116,766	3,123,957	131242			
x 4/3 to get 4 P.B.	1,362,490		5,489,022		174990			
Singke Power Block			1,372,255					
Single Transmuter				520,660				
Single T-G		330,936						

Table F.4. One Power Block FOAK Station

1 Power Block FOAK data, Table 8-1, GEFR-00940, March 1995. (Thousands of 1994 dollars)

WBS No.	BOP	Turbine-Gen. (1)	Power Block(1)	Transmuters(2)	Site Support (2)	BOP/Total	T-G/BOP	S.S./BOP
20	9,140							
213		9,678		-				
21	31,171			105,518				
22	-	-		403,028				
23	94,053	94,053		1,371				
24	28,973	28,973		18,803				
25	14,473			11,314				
26	16,899	16,899		-				
Direct Costs	194,709	149,603		540,034	45,106	0.2650	0.7683	0.2317
Indirect	120,457	92,552		216,658	27,905			
Base Const.	315,166	242,155		756,692	73,011			
Contingency	32,136	24,691		150,290	7,445			
Total O.N.C.	377,455	266,847		906,982	80,455			
IDC	62,289	47,859		172,761	14,430			
Total Capital Cost	439,744	314,706		1,079,743	94,885			
w/Addnl. 10% contg.	483,718	346,176	1,533,894	1,187,717	104,374			
Escalate to 1999	547,230	391,629	1,735,294	1,343,665	118,078			
FOAK (1) Single Units		391,629		671,832	118,078			
FOAK(3) Single Units		330,936		520,660	174,990			
NOAK(3) Single Units		301,608		430,101	163,325			

Table F.5. Three Power Block NOAK Station

3 Power Block NOAK data, Table 8-4, GEFR-00940, March 1995. (Thousands of 1994 dollars)

WBS No.	BOP	Turbine-Gen.(3)	Power Block(3)	Transmuters(6)	Site Support(3)	BOP/Total	T-G/BOP	S.S./BOP
20	10,753							
213		27,216		-				
21	50,447			246,446				
22	-	-		817,097				
23	274,953	274,953		1,569				
24	58,067	58,067		42,629				
25	20,148			15,399				
26	39,622	39,622		-				
Direct	453,990	399,858		1,123,140	54,132	0.2879	0.8808	0.1192
Indirect	204,979	180,538		392,092	24,441			
Base Const.	658,970	580,396		1,515,232	78,573			
Contingency	62,322	54,891		300,606	7,431			
Total O.N.C.	721,292	635,287		1,815,838	86,004			
IDC	104,242	91,813		257,888	12,429			
Total Capital Cost	825,534	727,100		2,073,726	98,433			
w/Addnl. 10% contg.	908,088	799,810	3,080,908.21	2,281,098	108,277			
Escalate to 1999		904,825	3,485,431.46	2,580,607	122,493			
x 4/3 to get 4 P.B.			4,647,241.94		163,325			
Single Power Block			1,161,810.49					
Single Transmuter				430,101				
Single T-G		301,608						

Distribution

No. of Copies

OFFSITE

4 U.S. Department of Energy Headquarters
Washington, D.C. 20585
ATTN: J. Bresee
W. Bishop
D. Goodwin
J. Herczeg

4 Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
ATTN: D. Crawford
D. Hill
J. Laidler
D. Wade

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973
ATTN: M. Todosow

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720
ATTN: D. Hoffman

Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550
ATTN: C. Walters

No. of Copies

4 Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
ATTN: E. Arthur
G. Lawrence
G. Van Tuyl
F. Venneri

L. Burris
206 Douglas Avenue
Naperville, IL 60540-4410

C. Ehrman
6 Warwick Lane
Basking Ridge, NJ 07920-2243

T. Myers
27 Industrial Blvd, Unit E
Medford, NY 11763

ONSITE

13 Pacific Northwest National Laboratory

M. R. Shay	K7-94
D. B. Shipler	K3-54
S. M. Short	K7-94
R. I. Smith	K7-94
J. K. Tarantino	K9-41
J. C. Wiborg	K7-74
Information Release (7)	