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Economics of National Waste Terminal Storage Spent Fuel Pricing Study

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May 1978

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SUMMARY

In this report the methodology for equitably pricing commercial nuclear spent fuel management is developed, and the results of four sample calculations are presented. The spent fuel management program analyzed in this study places encapsulated spent fuel in bedded salt while maintaining long-term retrievability. System design was intended to be reasonable but not optimum. When required, privately-owned Away From Reactor (AFR) storage is provided and the spent fuel placed in AFR storage is eventually transported to final storage. Applicable Research and Development and Government Overhead are included for completeness of cost recovery.

The cost of each component by year was estimated from the most recent applicable data source available. These costs were input to the pricing methodology to establish a one-time charge whose present value exactly recovered the present value of the expenditure flow. The four cases exercised were combinations of a high and a low quantity of spent fuel managed, with a single repository (venture) or a multiple repository (campaign) approach to system financial structure. Each flow of spent fuel was carefully traced to assure that receiving, processing, and capacity constraints were not exceeded.

The price for spent fuel management calculated in this study ranged from 116 to 152 dollars (1978) per kilogram charged initially to the reactor. The effect of spent fuel receiving rate on price is illustrated by the fact that the extremes of price did not coincide with the cases having the extremes of undiscounted cost. These prices for spent fuel management are comparable in magnitude to other fuel cycle costs. The range of variation is small because of compensating effects, i.e., additional costs for high early deliveries (AFR and transportation) versus lower present value of future revenue for later delivery cases. The methodology contains numerous conservative assumptions, provisions for contingencies, and covers the complete set of spent fuel management expenses.

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1.0 INTRODUCTION

1.1 PURPOSE

The recent Administration decision to defer reprocessing commercial spent nuclear fuel generates a national requirement for an alternative spent fuel management method for electric utilities. Numerous alternatives have been advanced involving various storage schemes. It is assumed that basic options are familiar.

This study outlines the basic economic issues relating to one such alternative, that of ultimate placement of spent fuel in bedded salt with long-term retrievability. The purpose of this study is to provide an equitable commercial spent fuel management pricing procedure for future use, and to exercise this procedure in four cases of interest to generate illustrative prices for spent fuel management.

Three principal ground rules have been adhered to in this study. First, equitable pricing has been defined as that price which leads to a revenue cash flow the present value of which exactly recovers the present value of all associated costs. This is consistent with the legislative requirement to recover all costs and is interpreted to include all research and development, government overhead and post operational activities attributable to commercial spent nuclear fuel management as well as direct program costs.

The second principal ground rule is that the price developed be a one-time charge with no retroactive adjustments for flow or cost estimation changes. Adjustments will be necessary, however, and since the future customers will generally be the same as existing customers, little inequity can arise from this ground rule.

Finally, this study takes no credit for the uranium or plutonium content of the accepted spent fuel. This ground rule is consistent with the current policy of indefinite deferral of reprocessing.

1.2 BACKGROUND

This task began with the award by the Office of Waste Isolation (OWI) of a contract to the TRW Energy Systems Planning Division to develop, program, and exercise a spent fuel storage cost model.

Subsequently, DOE formally announced its plans to accept spent fuel in return for a one-time charge after a five-year notification period. The methodology and procedures for calculating the one-time charge were to be published in the Federal Register along with an initially proposed price for comments from all interested parties.

In view of this announcement, OWI added three tasks to the TRW contract to collect additional data and develop the methodology required to calculate four cases of one-time charges for spent fuel management. The system design for these cases was to be reasonable, but no attempt was to be made to optimize all variables. The scope was limited in time and other resources in order to provide timely response. This study is the output of these additional tasks.

1.3 REPORT OUTLINE

This report begins with an overview of the total system (Chapter 2) and a description of the assumptions and data sources of each cost center for which costs are included (Chapters 3-8). Following this, the spent fuel flow and scenario assumptions are enumerated in Chapters 9 and 10. The pricing methodology combining the input data to form results is contained in Chapter 11 and the results are presented and interpreted in Chapter 12. Detailed cost, price, and methodology data are reserved for the Appendices.

2.0 SYSTEM DESCRIPTION

This chapter describes, in general, the system to which the ground rules enumerated in the Introduction were applied to yield scenarios for calculation of a one-time charge for storage and disposal of spent fuel. It provides a concise overview of the study interrelationships and boundaries. More detail on each system component, including numerical values which were assumed, will be found in the chapters which follow.

2.1 SYSTEM OVERVIEW

The spent fuel management system used in this study was broken down into six convenient collection categories called cost centers. The interrelation of these cost centers is illustrated in Figure 2-1. Spent fuel from commercial reactors is accepted FOB at the applicable first system component (AFR or geologic repository) at a rate determined by the scenario being studied (Chapter 10). Encapsulated retrievable spent fuel will be placed in bedded salt at the geologic repository beginning in late 1985. Spent fuel is placed at its design rate, or at the rate at which spent fuel is received from both U.S. and foreign sources if no other source exists. Annual spent fuel acceptance rate is increased to the design rate by accepting the existing backlog (2270 MTU in 1976) of spent fuel or by accepting spent fuel previously placed in AFR storage when these sources are available. Transportation of spent fuel from the AFR to the repository is included as a cost center. Finally, research and development and government overhead are included for technical and managerial completeness.

The AFR, encapsulation, and geologic repository cost centers are facility oriented. They contain costs in each of the expenditure categories, capital, operations and maintenance, and trust funds. The transportation, research and development, and government overhead cost centers are service oriented. They contain costs for their services categorized as "Other", for separability from those of the facility cost centers. All these costs with their related spent fuel flows will be found in detail in Appendix A.

Figure 2-1. Spent Fuel Management System Overview

2.2 CONSTRAINTS

The AFR, encapsulation facility, and geologic repository all have receiving or processing rate constraints expressed in annual metric tons of uranium. The AFR and geologic repository also have total capacity constraints. The numerical values of these constraints will be found in Chapter 9. All detailed flow quantities have been carefully examined to assure that these constraints have not been violated.

Geologic repository total capacity has the additional characteristic of varying with the age of the fuel emplaced in it. This variation has been accounted for by using data from reference III-3 in the capacities of each case. Furthermore, geologic repository receiving rate constraint has a five-year initial value for phase-in which triples to its maximum value for all subsequent (to capacity) years.

Second encapsulation and second geologic repository facilities have higher constraints than the first facilities; however, no capital cost increase has been added. This is equivalent to assuming some savings due to learning effects in facility construction. The validity of this assumption is uncertain, but it is the most reasonable assumption available based on present expectations.

Rate constraints have delayed completion of backlog acceptance and increased AFR capacity requirements. Capacity constraints require determining the number and utilization of AFR storage facilities and the timing of second repository construction. In each case, second repository timing has been carefully examined not only for flow constraints, but also for the effect on first repository closing which was delayed in both multirepository cases because of the acceptance of part of the flow by the second repository.

2.3 SCENARIO

The spent fuel management system described above was exercised with four scenarios representing all combinations of two fuel input rates, and two approaches to the financial structure of the price. For illustration, cooling delays of five and ten years from the discharges in reference IX-1 were used as high and low baselines to which were added existing backlog and 10 percent of candidate foreign fuel. Yearly breakdowns of these flows will be found in Chapter 10.

The first approach to financial structure was to treat all elements relating to the first repository only through its closing. This approach, called venture methodology, minimizes required assumptions and creates the approach most firmly based in current data. The second approach selected was to treat all required elements until a fixed year in the future (2000 for this study). The approach, called the campaign methodology, could be used on a continuing basis to price spent fuel management in the future by changing the year of termination. This methodology requires assumptions about second repository and related activities, and a treatment of partially used facilities at termination. The two methodologies provide unique insights; therefore, both were exercised to provide results of greatest interest.

2.4 TRUST FUNDS

All decommissioning and post operational activities in the price calculations of this study were included through trust funds present valued into the last year of the applicable facility operation or the termination year for partially used facilities. The AFR, encapsulation, and geologic repository cost centers are each assigned their own decommissioning trust fund, but only the geologic repository cost center was provided a post operation trust fund. Thus, there were four types of trust funds.

The cost distribution by year for each decommissioning trust fund is provided in the applicable facility's chapter of this report as is its present value which can be seen in the cost data in Appendix A.

The post operation trust fund has two purposes. First, it supports maintenance operations after the facility reaches capacity but before decommissioning. Second, it provides contingency funds for possible activities after decommissioning which remain undefined at the time of this study. It is assumed that the former purpose will be the most financially demanding and, therefore, will serve to determine the size of the trust fund. A detailed analysis of required post operational activities is beyond the scope of this study.

Partially used facilities in the termination year require partial trust funds to assure equitable cost distribution to each user. For this purpose, the full trust funds described above and enumerated in the facility chapters were first reduced by the unutilized fraction of the facility (i.e., multiplied by the fraction of capacity filled). They were then discounted from the closing year of the facility (after the termination year) to the termination year of the scenario. The resulting values can be seen in the cost details of Cases 2 and 4 in Appendix A.

3.0 GEOLOGIC REPOSITORY

This chapter enumerates the assumptions, data sources, and methodologies used to determine the costs of the geologic repository. There are four categories of costs used for each repository:

- Capital costs
- Operations and maintenance (O&M) costs
- Decommissioning costs
- Post operational costs.

Each category of costs for each repository is displayed in detail in Appendix A.

3.1 ASSUMPTIONS

This study assumes that the geologic repository is to be located in underground bedded salt deposits and will encompass 2000 acres. The facility will accept spent fuel beginning in late 1985 at an initial design rate of 6000 fuel assemblies (1780 MTU) per year. After receiving spent fuel at this rate for 5 years, the rate will triple to 18,000 fuel assemblies (5320 MTU) per year. This study was conducted with the design rate as maximum spent fuel input to the repository. Each repository will provide the facilities and supporting utilities for mining, storing, and backfilling the salt; ventilating all shafts and tunnels; receiving spent fuel either by truck or rail; the emplacement of the canistered fuel in salt while maintaining the retrievability.

The repository is assumed to be in substantial conformance with the Generic Environmental Impact Statement on Commercial Waste Management. However, specifics of this statement have not been released for public dissemination at the time of this study. Where necessary for display, details were drawn from reference III-1.

The capacity of the repository is determined by the mode of operation and the age of the fuel being emplaced. Each first repository will be operated in a long-term retrievable mode. Capacity in this mode of operation is determined from room closure limits. Second repositories,

operating in the five-year retrievability mode, are limited by total heat energy delivered to the salt. Assuming ten-year-old spent fuel is emplaced in the second repository operating in this mode, the capacity is 104,700 MTU. Fuel limits for the first repository are 44,200 MTU for five-year-old fuel (reference III-2) and 52,500 MTU for ten-year-old fuel (reference III-3). Emplacement of these capacities of fuel results in equivalent heat energy delivered to the salt over a 25-year period.

3.2 DATA SOURCES

The basic source of geologic repository capital, O&M, and decommissioning expenditures is Mr. C. D. Zerby's letter of January 6, 1978 entitled "Spent Fuel Repository Cost Estimates" (reference III-4). The letter details the costs for operating in both five-year and 25-year retrievability modes. These costs include an undesignated capital contingency factor of 22 percent. Since the current study is of indefinite retrievability, the 25-year retrievability case was used as the baseline.

To obtain complete consistent costs for this study, capital costs from Mr. Zerby's letter were modified in two ways. First, these costs were increased by 10.2 percent to account for owner's cost. This factor of 10.2 percent was derived from the non-reactor owner's cost calculation used by Bechtel. (see references III-5, IV-1, IV-2, and V-3). For explicit details of these factors, see Table 3-1.

TABLE 3-1.
Details of Bechtel Owner's Cost Methodology
(Non-Reactor Nuclear Facilities)

CATEGORY	FACTOR
Land	1.8%
Equip.Spares	0.6%
Permits and Licenses	1.2%
Interest During Construction	18.0%
Startups	0.9%
Initial Inventories	0.9%
Eng. Ops. & Accounting	2.4%
Manuals, Clothing & Stock	3.0%
Insurance	1.2%
	<u>30.0%</u>

When interest during construction and land costs were excluded from geologic repository costs, the remainder was 10.2 percent. These exclusions were required in the computations because the former duplicates the present value calculation and the latter is specifically estimated within the capital costs cited in reference III-4. These owner's costs were distributed by year in proportion to the other capital costs detailed by the letter.

The second modification to reference III-4 capital costs was the inclusion of operator startup expense. These costs, including their distribution by year, were provided by OWI and are enumerated in Table 3-2.

TABLE 3-2.
Geologic Repository Operator's Startup Expenses

YEAR	1978 \$M ¹
1980	1.
1981	2.
1982	5.
1983	10.
1984	12.
1985	15.
TOTAL	45.

The two modifications, which total \$96.M, (1978) form the "Administration Costs" category in Table 3-3. This table details the total geologic repository capital costs. No additional contingency was provided due to these cost increases.

One modification to reference III-4, 25-year retrievability operations and maintenance costs, has been made for this study. The costs for excavation have been stretched from three to seven years as used in the five-year retrievability case. The change reflects only the conservative use of underground mining equipment and does not impact the emplacement rate of spent fuel. This modification results in no change in the total undiscounted costs. However, the expenses for the first three years show an approximate reduction of 10 percent while an increase of approximately 7 percent is shown over the next four years.

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¹For computational simplicity, 4th quarter 1977 dollars were assumed equal to 1978 dollars.

Table 3-3. Geologic Repository Capital Costs (1978 \$M)

CATEGORY ¹		TOTAL	78	79	80	81	82	83	84	85
1.0.0	PLANT AND CAPITAL EQUIP.									
1.1.0	ADMINISTRATION COSTS ²	96.0	.03	.25	3.01	10.22	18.13	21.37	20.60	22.39
1.2.0	LINE ITEM CONSTRUCTION									
1.2.1	ENG. DESIGN AND INSPECTION	54.34		.98	8.53	20.47	12.70	4.62	3.65	3.45
1.2.2	LAND AND LAND RIGHTS	11.25	.26	1.0	7.5	2.49				
1.2.3.0	BASIC CONSTRUCTION COSTS									
1.2.3.1	IMPROVEMENTS TO LAND	30.865				13.071	15.374	2.42		
1.2.3.2	BUILDINGS	21.845				1.307	6.653	2.833	6.366	4.686
1.2.3.3	OTHER STRUCTURES	0								
1.2.3.4	SPECIAL FACILITIES	169.8				9.43	36.608	53.296	36.947	33.469
1.2.3.5	UTILITIES	46.48				16.447	19.314	6.639	3.583	.497
1.2.4	STANDARD EQUIPMENT	72.93				2.446	14.298	21.06	18.202	16.924
1.2.5	REMOVAL LESS SALVAGE	0								
1.2.6	CONTINGENCY ALLOWANCE	92.49	.06	.45	3.64	14.9	23.82	20.62	15.60	13.40
TOTAL ³		596.0	.35	2.68	22.68	90.77	146.9	132.86	104.95	94.81

¹ Budget category breakdown assumes multiple category A&E projects charge proportionately in each year.

² No additional contingency allowance has been added to reference III-4 costs due to this expense.

³ This cost data is shown in the detailed cost inputs of Appendix A in all four cases.

For years in which the full design receipt rate is emplaced in the repository, reference III-4 O&M costs, modified as above, were used. For years in which an emplacement rate of less than that designed occurred, a more complex methodology was required. This low rate of emplacement occurred when the spent fuel receipt rates were below the design rate and there was no AFR content or backlog. For the years in which this lower rate occurred, the O&M costs for the repository were estimated in three parts.

- The time-related costs of capital equipment (surface and mining), mine excavation, and salt storage were assigned their value from reference III-4 by year from the repository opening.
- The rate-related annual costs of general mine support, waste handling, surface support, storage maintenance, equipment maintenance, personnel, utilities, and materials and supplies were estimated by manual interpolation of Figure 3-1 as a function of the annual received fuel. The figure illustrates a smooth curve through the four values individually estimated by OWI and documented in reference III-6.
- Retrieval sleeves and plugs costs were estimated at \$7179 per MTU for retrievable operations from reference III-4. All but the maximum rate phase of the second repository maintained long-term retrievability.

The complete set of O&M costs for the geologic repository is displayed in Appendix A.

Repository decommissioning costs were taken to be the last seven years of costs in reference III-4 for the 25-year retrievability case.

Figure 3-1. Variable Geologic Repository Annual Cost
3-6

Table 3-4 enumerates these costs below.

TABLE 3-4.
Geologic Repository Decommissioning Costs

Year	1978 \$ M
1	34.615
2	26.496
3	26.373
4	26.183
5	35.790
6	26.988
7	21.596
TOTAL	198.041

These costs were discounted at 6.5 percent to the last year of operations (year 0 above), then charged to each closed repository. This discounting procedure results in \$156.56 M. For partially filled repositories in the multirepository campaign methodology, this value is reduced by unutilized capacity fraction and discounted to the horizon year.

To support activities after final spent fuel emplacement, a post operational annuity has been provided. This annuity has been designed to produce exactly the average yearly expense shown during the 12 years of maintenance operations in reference III-4 when invested at 6.5 percent. It is assumed that these costs are the largest to be encountered; the annuity is conservatively estimated to produce the value of \$24.78M (1978) yearly. Since the annuity is charged in the last year of operations but is not needed until the following year, it is discounted one year at a rate of 6.5 percent which results in \$357.385 M. This value was also reduced by the unutilized capacity fraction and discounted to the horizon year for partially used facilities in the multirepository campaign methodology case. After decommissioning, this trust fund is perpetually available to provide funds for any contingency relating to the repository.

4.0 ENCAPSULATION FACILITY

This chapter contains the assumptions and data sources used to estimate capital, O&M, and decommissioning costs of the encapsulation cost center. The estimated costs for each case will be found in Appendix A.

4.1 ASSUMPTIONS

The encapsulation of spent fuel is assumed to take place at the geologic repository site. As the spent fuel is received, assemblies are placed in canisters which are then backfilled with sand, welded closed, tested for leaks and transported to temporary storage or to the canistered waste shaft of the geologic repository. This facility also has the ability to overpack failed fuel canisters with a second canister, and to weld, test, and transport these overpack canisters in a manner similar to standard canisters. The estimated annual capacity to encapsulate fuel is commensurate with the geologic repository receiving rate.

A water storage basin area is required to provide process surge capacity for encapsulation. A two-month processing surge capability is considered adequate for this purpose.

Fuel characteristics are assumed to allow two BWR fuel assemblies per canister, but only one PWR assembly per canister.

Finally, three percent of fuel arriving at the facility is assumed failed for estimating overpack requirements.

4.2 DATA SOURCES

Capital cost data for the encapsulation facility is based primarily on a scaling up of reference IV-1 from 2000 MTU/year to 6000 MTU/year. Reference IV-1 contains unspecified contingencies, which are assumed to be 22 percent for comparison. Costs in this reference also exclude receiving facilities and supporting utilities since the reference is on the site of a large storage basin. The referenced facility contains three hot cells for processing. One is reserved only for failed fuel. Therefore, tripling capacity requires six cells for unfailed fuel and retaining the single cell for failed fuel for seven channels. Each category of cost in the referenced facility was scaled up using the ratio

Table 4-1. Encapsulation Capital Cost Scaling
(2000 MTU/Year Increased to 6000 MTU/Year)

CATEGORY	1976 \$M	FACTOR USED	FACTOR VALUE	1978 \$M ¹
Major Equipment	11.3 ²	Number of Major Cranes	2.0	26.1
Building & Structure	29.7 ²	Feet of Reinforced Concrete	2.4	82.3
Bulk Materials	6.6 ²	Number of Channels	2.333	17.8
Site Improvement	0.7 ²	Enclosed Area	2.171	1.8
				(128.0)
Water Basin-1000 MTJ				
Major Equipment	2.3 ²	None	1.0	2.7
Building & Structure	11.3 ²	Area of Pool Surfaces	0.5577	7.3
Bulk Materials	2.4 ²	None	1.0	2.8
Site Improvement	0.5 ²	None	1.0	.6
Storage Baskets	--	Dupont Estimate	\$6.2M (1978) per 1000 MTU	6.2
				(19.6)
Indirect	29.7	% of Above	45%	66.4
A&E	19.1	% of Above, Including Indirect	20%	42.8
Owner's Cost	13.8	% of Above, Exclude Interest During Construction	12%	30.8
				(140.0)
TOTAL	127.4			287.6

¹Inflated using the chemical industry plant capital cost index

²Unspecified contingency included.

of a measurable appropriate architectural factor in the reference facility to the same factor in the enlarged facility. Water basin storage for two months' surge (1000 MTU) was estimated from reference IV-2 with the Building and Structures category scaled, but with other categories remaining as in the basic reference (2000 MTU). Storage baskets for this water basin were estimated using costs from reference V-1.

Table 4-1 lists the names and values of the factors used and the complete calculation of encapsulation facility capital costs. These costs were distributed by year using TRW's best judgment after examining in detail the construction schedule contained in reference IV-1 and the schedule of the colocated geologic repository. Table 4-2 contains the resulting capital costs by year.

Table 4-2. Encapsulation Facility Capital Costs by Year
1978 \$ M

	TOTAL	78	79	80	81	82	83	84	85
ADMINISTRATION COST	30.8				3	5	8	10	4.8
MAJOR EQUIP.	26.1					8.2	12	5.9	
BUILDINGS & STRUCTURES	82.3				7	15	25	30.1	5.2
BULK MATERIAL	17.8					3	6	7.8	1
SITE IMPROVEMENTS	1.8				0.6	0.5	0.4	0.3	
INDIRECT	66.4				2	13	21	26	4.4
A&E	42.8				8	16	8	6	4.8
WATER BASIN STORAGE	19.6					5	7	6	1.6
TOTAL	287.6				20.6	65.7	87.4	92.1	21.8

Table 4-3. Encapsulation Facility Staff Requirements

	FIRST SHIFT	EACH ADDITIONAL SHIFT
OPERATORS		
CELLS FOR UNFAILED FUEL	12	12
CELLS FOR FAILED FUEL	3	-
HOLDING CELLS	3	3
HANDLERS	6	6
FOREMEN	3	3
SUPPLY		
GENERAL	2	1
CONTAINERS		
FEED TO LINE	3	1
REC. & INSP.	2	-
REPAIR	1	-
FOREMEN	1	-
SHOP TECHNICIANS		
WARM	2	-
MECHANICAL	3	1
ELECT. & INST.	3	1
SUPERVISOR	1	-
MAINTENANCE		
JANITORIAL	4	1
UTILITIES	2	2
PROCESS	2	2
FOREMEN	2	1
MISCELLANEOUS		
GUARDS	3	2
ACCOUNTING	2	2
HEALTH PHYSICS	2	2
CLERICAL	3	-
SUPERVISORS	4	1
ENGINEERS	2	-
MANAGEMENT	3	1
TOTAL	74	42

Encapsulation operating costs were estimated in two parts; first, personnel, and second, materials. Personnel costs were estimated by a detailed examination of the reference IV-1 facility resulting in the staff requirements enumerated in Table 4-3. Each shift shown in Table 4-3 is assumed able to operate two hot cells for unfailed fuel. All failed fuel operations are assumed to take place during the first shift since only 3 percent of capacity enters this cell. Shifts were assumed to be required in integer increments regardless of any excess capability this provided. Table 4-4 shows the personnel costs to encapsulate fuel as a function of capacity available that results from these assumptions.

Table 4.4 Encapsulation Personnel Cost As A Function Of Capacity Available

CAPACITY (MTU/YR)	PERSONNEL	COST (1978 \$ M) ¹
2000	158	6.32
2660	200	8.0
3330	242	9.68
4000	284	11.36
4660	326	13.04
5330	368	14.72
6000	410	16.4

For further conservatism, it is assumed that when required capacity is reduced, personnel will be retained if capacity later increases.

Material cost of the encapsulation cost center O&M expense was estimated based on the following unpublished data received from the OWI staff.

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¹ @ \$40,000 per person--source DuPont, Savannah River Operations

Table 4.5 Encapsulation Material Costs
(1978 \$)

CANISTER	\$400
TOP	\$ 75
FREIGHT	\$ 40
SAND/CANISTER	\$ 2
OVERPACK	\$600
OVERPACK TOP	\$100
OVERPACK FREIGHT	\$ 60

Combining these with the assumed fuel elements per canister, the ratio of types of fuel elements shown in reference III-3 and the 3 percent overpack rate results in an average cost per canister of \$524 or \$1252 per MTU.

Combining personnel and material costs, the O&M Cost of encapsulation as a function of encapsulated fuel is shown in Figure 4-1.

Decommissioning of the encapsulation facility is assumed to cost 10 percent of the total capital cost of the facility. This factor is commensurate with the surface decommissioning cost proportion of surface capital cost for the geologic repository. These costs have been distributed by year in proportion to the demolition contractor costs shown in reference III-4. The resulting decommissioning costs are shown in Table 4-6.

These costs have been discounted at 6.5 percent to the last year of operations (year 0 in Table 5-6) and the resulting value (\$19.94M) shown in the cost data in that year for each closed encapsulation plant. The previously defined partially used facility methodology has been applied to this value for encapsulation facilities which remain open after the horizon year of the continuous methodology scenarios.

Complete annual encapsulation O&M and decommissioning costs for each case can be seen in Appendix A.

Figure 4-1. Encapsulation O&M Costs vs. Fuel Encapsulated

Table 4-6. Encapsulation Decommissioning Costs

YEAR	COST (1978 \$ M)
1	3.03
2	3.44
3	3.4
4	3.39
5	4.52
6	4.4
7	3.57
TOTAL	25.75

5.0 AWAY FROM REACTOR STORAGE

This chapter presents the assumptions and data sources used to estimate the Capital, O&M, and Decommissioning costs for the Away From Reactor (AFR) storage cost center. In this study, this cost center is required only in the cases of high receipts. It should be noted, however, that AFR storage capacity presents a reasonable contingency capability and must be considered on the basis of this criteria as well. Furthermore, since AFRs are assumed to be privately owned, the estimated costs in this chapter must not be confused with the charges to the government generated from these AFR costs using the Pricing Methodology described in Chapter 11. Appendix A displays the annual costs discussed only in this chapter. Charges to the government also include operator's return, taxes, and insurance, which are not addressed in this chapter.

5.1 ASSUMPTIONS

AFR storage is required if a scenario calls for fuel to be delivered to the government prior to the availability of geologic repository storage or in excess of repository receiving capability. If required, AFRs are assumed privately owned with after tax discounted return to the operator of 12 percent¹. Dispersal of AFRs throughout the country was desirable to minimize transportation costs and to provide more easily available and backup emergency storage. In addition, building smaller facilities delays some expense to later years. However, economy of scale is gained by building facilities that are as large as possible.

Based on the capacity required by the flow scenarios discussed in Chapter 10, this study chose a middle range as the expected outcome of more detailed analyses of the above factors, specifically two 7000 MTU capacity AFRs.

AFR receiving rate was assumed to be 2000 MTU/yr. However, the study did not wish to restrict the mix of truck and rail receipts. Therefore, provision was made to build greater than 2000 MTU/yr. capacity but not use it, solely to provide both sufficient truck and rail receiving capacity.

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¹Note that all other costs (including AFR charges to the government) were discounted at 6.5 percent.

Finally, small capacities have been retained unused in each AFR so that surge storage will be available if necessary. The actual utilization of each AFR in this study is 91.4 percent. The first AFR is filled to this level before the second AFR is required, to defer capital expense as long as possible. Both AFRs are emptied simultaneously to uniformly distribute transportation and available capacity throughout the country.

5.2 DATA SOURCES

Figure 5-1 summarizes AFR capital cost from references V-1, 2 and 3 on a consistent basis. This figure illustrates a scaling effect with slope generally decreasing slightly with increasing capacity and good correlation among the absolute levels of cost. Therefore, the DuPont values (reference V-1) were selected for use in this study. Two adjustments were made to the data as presented by DuPont. First, owner's cost of 10.2 percent, which excludes land and interest during construction, was added for completeness and consistency with other cost centers. Second, storage baskets capitalized after start of operations by DuPont were included before the start of operation for this study. The latter assumption was made only for conservatism and did not change the cost of the facility, only its distribution by year. The basic contingency allowance of 25 percent (reference V-1) was not increased due to these changes.

The pricing methodology developed in Chapter 11 required separate costs for land and working capital. Land costs were already contained in the DuPont data. Working capital was estimated as one month's average expenses over the life of the facility and ranged from \$6.19 M to \$6.58 M. A complete display of AFR capital costs to the owner (for pricing methodology to derive cost to the government) is shown in Table 5-1.

AFR O&M costs were also taken from reference V-1 although they are supported in absolute level by reference V-2. Since AFR operations are almost entirely personnel oriented, no variation was considered due to changes in fuel received, so sufficient personnel were provided to handle maximum loads in all years. Therefore, in all years or partial years of AFR operations, \$6 M (1978) per AFR was charged for operations. During years of surveillance only, this value was reduced to \$4 M (1978) per reference V-1. Both of these values used the average 1978 Savannah

Figure 5-1. AFR Capital Costs

Table 5-1. AFR Capital Costs
 7000 MTU Capacity, 3000 MTU/yr Receiving Rate
 Basic Source - Reference V-1
 Owner's Cost - Bechtel Methodology
 1978 \$ M

CATEGORY	TOTAL	YEAR 1	YEAR 2	YEAR 3	YEAR 4
CAPITAL ¹	273	15	34	111	113
PLANT	204	13	17	87	87
STORAGE BASKETS	44		14	14	16
OWNER'S COST	25	2	3	10	10
LAND ¹	5	3	2		
TOTAL	278	18	36	111	113

¹Inputs to Chapter 11 Price Methodology for computation of return, taxes, and insurance

River burdened cost per person of \$40,000. The total undiscounted 1978 costs of AFR operation in the two cases where AFRs were required were \$160 M and \$136 M. Display of these costs by year will be found in Appendix A.

AFR decommissioning costs were estimated to be 10 percent of capital cost excluding owner's cost in constant dollars. This factor is commensurate with the surface facility decommissioning cost percentage of the geologic repository (reference III-4). These costs were distributed by year by TRW according to Table 5-2.

Table 5-2. AFR Decommissioning Costs
 7000 MTU Capacity
 3000 MTU/yr Receiving Rate

YEAR	1978 \$ M
1	0
2	9
3	8
TOTAL	25

These costs were discounted at 6.5 percent into the last year of AFR operation (year 0 above, result \$22.07 M) and charged in that year in the price calculation. Scenario ground rules required all AFRs to close within the years considered, so no partial trust fund methodology was applied to this cost center.

6.0 TRANSPORTATION

This chapter presents the assumptions and data sources used to estimate the transportation cost of spent fuel between the AFR and the repository. Spent fuel is received FOB at the designated first facility of the system. Therefore, total cost to a utility exceeds the costs shown in this document by the cost to transport its spent fuel over the first transportation link.

6.1 ASSUMPTIONS

AFR to repository transportation is assumed to be entirely by dedicated trains using IF-300 casks. Freight cost, dedicated train cost and cask leasing cost are addressed in this cost center. Costs for train service and cask lease, incurred in transporting spent fuel between the AFR and the repository, are affected by:

- Freight Rates
- Dedicated Train Rates
- Daily Cask Lease Rate
- Train Speed
- Facility Location.

Freight cost was calculated by summing loaded and empty costs for the full train. A 10 percent discount was included based on provisions of the ICC Act, Part I Section 22 which permits negotiated rates with government agencies. Dedicated train costs are assumed to be the product of cost per mile times distance for all segments (rail lines) of both loaded and empty trips.

Daily cask lease cost depends on the availability and replacement cost of IF-300 casks. All IF-300 casks and rail cars required are assumed to be prefinanced and available from the private sector with owner's profit included in the cask lease daily rate. Cask lease costs for a full train are assumed to be the product of cask lease daily rate times the length of the cask lease period. Facility locations assumed in this study

for distance determinations were:

- AFR #1 - Savannah River, S.C.
- AFR #2 - Richland, Washington
- Repository - Southwestern U.S.

Division of distance by average speed of the dedicated train plus loading and unloading time yields the length of the cask leasing period. Finally, average cost of transporting a metric ton of uranium between the AFR and the repository is the total of the above rail service charges and the cask lease charge divided by total uranium moved in metric tons. The AFRs are assumed to be emptied uniformly in each year. Therefore, the average cost per MTU of the two facilities was multiplied by the uranium shipped to obtain the annual cost.

6.2 DATA SOURCES

The principal source of data for transportation costs is reference VI-1 which details research by OWI personnel into current nuclear transportation costs. This reference gives freight and dedicated train rates, IF-300 cask weights, cask capacities, train size and a range of daily cask lease rates. Both freight and dedicated train rates were discounted to account for any cost negotiations with the railroads. Additional research by OWI resulted in the following assumptions:

- Train speed will be 160 miles per day.
- Five day loading/unloading time.

This gives a greater train speed than is normally experienced on regular trains, but is somewhat less than the train speed that could be expected if all queueing were eliminated from regular train service. Total weights were used for calculating shipping costs; however, only the weight of uranium initially charged to the reactor was divided into metric tons of uranium shipped to calculate cost per ton. Fuel element breakdowns for PWR and BWR were calculated separately and combined using 40.2 percent PWR and 59.8 percent BWR derived from reference III-3. Table 6-1 is a summary of both the inputs and the results of the calculations. It should be noted that cask lease cost constitutes more than 70 percent of all transportation costs. The yearly cost of transportation was calculated by multiplying the average total cost per MTU of \$32,529 by the yearly shipments. These costs will be seen in Appendix A. The total cost of transporting the 12,860 MTU AFR contents is \$417M (1978).

TABLE 6-1. TRANSPORTATION SUMMARY

	AFR #1	AFR #2
Inputs		
Freight Rate (\$/cwt)		
Loaded	5.68	7.62
Empty	5.31	7.15
Dedicated Train		
First Segment		
Rate (\$/mile)	19.69	17.93
Distance (one way miles)	640	1675
Second Segment		
Rate (\$/mile)	19.72	-
Distance (one way miles)	967	-
Cask Lease Rate (\$/day)	3000.	3000.
Cost (\$/MTU)		
Freight	4,094	5,502
Dedicated Train	4,371	4,145
Cask Lease	23,082	23,864
TOTAL	31,547	33,511

7.0 RESEARCH AND DEVELOPMENT

This chapter discusses the research and development (R&D) costs which are included in this study for complete recovery of all government costs. Assumptions made, coverage of the costs, and source of the data are enumerated to assure an understanding of the resulting impact on price. Identical R&D costs are included in all four cases.

Since government R&D funds have been and will be expended in support of commercial spent fuel management, their recovery through these management charges is reasonable and logical by evenly distributing the expense of nuclear electricity generation. R&D costs have been included for various geologic media in which spent fuel placement has been considered and for all interim management methods and processes under study or reasonably predictable. Certainly other reasonable estimates of commercial spent fuel R&D costs could be constructed. However, the coverage and representative values used here represent the best values available to date for pricing of commercial spent fuel management.

The costs include expenditures of the DOE's Office of Waste Isolation, Nevada Operations, and Richland Operations' terminal storage projects. Major programs contained in these costs include the Lyons, Kansas project, the Encapsulation Program, and the Spent Unreprocessed Fuel Facility Program. Both expended and predicted expenses are included. Expended R&D funds are not negatively discounted (inflated); however, future R&D is discounted for pricing purposes.

The source of the R&D cost values is reference VII-1. Figure 7-1 illustrates these values. The numerical values will be found in the detailed cost data of all four cases in Appendix A. Because of the sensitive nature of future budget projections, the detailed breakdown of these values was not available to TRW since they were not required for the calculation of a spent fuel management price.

Figure 7-1. Research and Development Cost

8.0 GOVERNMENT OVERHEAD

This chapter discusses the assumptions and data sources supporting the costs included in the government overhead cost center. These costs were included to assure recovery of all costs associated with the commercial spent fuel management program. They are intended to represent all non-R&D expenses to the government not directly associated with the operation of the other cost centers and, therefore, excluded from all other costs.

In estimating these costs, consideration was given to the overhead costs included in the price of uranium enrichment services provided by the government. This program is larger in cost than the spent fuel management program, but includes large amounts of purchased electricity. The number of facility cost centers is approximately the same. Therefore, it is assumed that annual government overhead costs will be identical to those of the enrichment program in the years in which spent fuel is received.

In years of capital construction, these or similar costs have already been accounted for as owner's cost in each facility cost center and in the R&D costs.

The enrichment program costs used were obtained from reference VIII-1. Table 8-1 enumerates the value of these costs.

Table 8-1. Government Overhead Annual Costs

CATEGORY	1978 \$ M
Community Support	1
Security	3
Government Support	9
TOTAL	13

The resulting cost data are shown for all four cases in Appendix A. Total undiscounted 1978 costs for the four cases range from \$195 to \$234M.

9.0 SPENT FUEL QUANTITY

This chapter presents the assumptions and data sources of this study relating to spent fuel discharged by reactors and constraints imposed on spent fuel handling by system components. These data will be combined with scenario assumptions in chapter 10 to yield complete spent fuel flows for four cases.

9.1 REACTOR DISCHARGES

This study assumes that U.S. reactor discharges will be those of reference IX-1. These discharges increase continuously as nuclear generating capacity increases to 380 GWe installed by the year 2000. This reference assumes conservative reactor characteristics.¹ Reference IX-1 further shows an existing backlog of spent fuel in 1976 of 2270 MTU.

Foreign fuel discharges were estimated in reference IX-2. Ten percent of candidate foreign fuel was assumed delivered to the spent fuel management system. A foreign backlog of 600 MTU in 1976, as shown in this reference, was also accepted. Table 9-1 summarizes the GWe installed and discharges assumed in this study.

9.2 STORAGE CAPACITY AND HANDLING CONSTRAINTS

The facilities costed in this study were set up to balance the capital building costs with the maximum system lifetime requirements. This section describes these constraints for each cost center involved which are:

- AFR
- Encapsulation
- Geologic repository.

The AFR storage capacity selected was near the midrange of the total capital cost relationship used. A limit of 2000 MTU per year was placed on the AFR spent fuel receiving capacity; sufficient capacity was costed to provide 3000 MTU per year receiving capacity. Both truck and rail

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¹For example, weighted average burn up = $27,089 \text{ MW}_t\text{D/MTU}$, capacity factor lifetime average = 56 percent.

Table 9-1 Nuclear Generating Capacity and Discharges

Year	U.S. GWe Installed	U.S. Discharge (MTU)	Foreign Discharge (MTU)
Prior	42.7	2270	600
1977	51.2	1050	300
1978	55.1	1230	200
1979	60.6	1380	400
1980	65.8	1510	300
1981	70.5	1660	400
1982	82.3	1790	400
1983	93.5	1990	400
1984	109.2	2280	500
1985	126.5	2620	500
1986	140.6	3040	600
1987	153.2	3450	700
1988	165.8	3790	700
1989	179.3	4120	800
1990	194.4	4440	1000
1991	210.2	4800	900
1992	227.0	5170	1100
1993	243.8	5560	1200
1994	262.7	5970	1200
1995	282.5	6390	1400
1996	302.3	6850	1400
1997	322.1	7320	1600
1998	341.9	7790	1600
1999	361.7	8250	1700
2000	379.7	8700	1800

receiving facilities are arranged to handle either mode of transportation selected by the utilities. This excess capacity also provides reasonable expectation of achieving the maximum receiving capacities as required in the early years.

In costing the encapsulation facility, scaling techniques were used which tripled the processing capacity of the base estimate. Chapter 4 gives a detailed description of this calculation.

The geologic repository costs were based on the following assumptions.

- Storage capacity meets original design specifications.
- Receiving constraints are not exceeded.

The constraints used to cost each facility are detailed in Table 9-2. Each facilities flow was examined; if constraints were violated, receipts were deferred by taking less backlog or by rearranging the facility schedule to provide additional capacity.

Table 9-2 Spent Fuel Handling Constraints

Facility	Receiving Rate (MTU/YR)	Capacity (MTU)
AFR	2000	7000 ¹
Encapsulation		
First	6000	N/A
Second	9000	N/A
Geologic Repository		
First		52,500 ²
Initial 5 years	1780	
Final	5320	
Second		104,700 ³
Initial 5 years	3000	
Final	9000	

¹Only 91.4 percent utilized

²For all 10-year-old retrievable fuel at emplacement, 44,200 for 5-year-old fuel

³Five-year retrievability

10.0 SCENARIOS

This chapter presents the detailed scenarios used to price four spent fuel management cases. Two scenario variables were combined for two values each. Assumptions regarding these variables are presented in the first two sections. The detailed spent fuel flows by year and by facility resulting from these combinations are presented and discussed in the final section. Detailed costs for each scenario will be found in Appendix A.

10.1 SPENT FUEL INPUT RATE

If most utilities choose to deliver as much spent fuel as permissible under government policy, the government spent fuel management system must be prepared for high early values, after a 5-year notification lag. This decision can be expected if utilities have confidence in the system and they find at-reactor storage impractical, too great a regulatory problem or too expensive. On the other hand, if utilities elect to retain their spent fuel for expected residual value and have or build sufficient storage at reactors, then the government spent fuel management system must be prepared for low delivery rates.

In order to create a high and a low delivery example, this study elected to examine cooling delays of five and ten years from the discharges defined in Chapter 9. Both foreign and U.S. fuel were delayed five and ten years; foreign fuel was accepted only through 1990. Thus the foreign receipts were also high and low, constituting 4000 and 1800 MTU, respectively. Both high and low flow cases accepted the identical pre 1978 U.S. and foreign backlogs of 4220 MTU (Reference IX-1 and IX-2). The earliest delivery occurred in the high flow cases only. Contracts were expected to be executed in 1978 for receipt of spent fuel in 1983.

Display and discussion of these complete flows is deferred to the end of this chapter because of their interrelationship with the second scenario variable. These flows must not be interpreted as forecasts of utility positions. No survey or analysis was conducted to estimate the best value. They are, however, illustrative of flows that the system might be required to process regardless of the source of the input and so they represent a reasonable baseline for analysis.

10.2 FINANCIAL STRUCTURE

Two approaches to financial structure formed the second variable for scenario construction. In the first approach, only those costs necessary to build, fill, and prepare for decommissioning and post operations for a single geologic repository are considered. Naturally, only spent fuel receipts up to the capacity of a single geologic repository are charged these costs. This approach was called venture methodology because it approximates the treatment of a single project, the first repository, as an entity. In the five-year cooling delay, high fuel input case, this methodology (case 1) required that the repository remain open one year (1997) beyond the receipt by the system of its cumulative spent fuel capacity in order to emplace the final quantity of AFR stored spent fuel. In the ten-year cooling delay, low fuel input case this methodology (case 3) results in costs through 2003 to reach capacity. Since all facilities are filled to capacity and completely utilized this methodology charged the full value of all trust funds and did not consider undepreciated value of facilities.

The second approach includes the cost of all system elements which would be required to manage all spent fuel expected to be received through an arbitrarily chosen horizon year and retain the ability for continuous operations. The costs through the horizon year are then combined with the receipts through the horizon year to determine the price of spent fuel management. Undepreciated value (negative cost) is taken in the final year for existing facilities (straight line over 10 years' depreciation was selected). Also, trust fund values are adjusted to recognize their inclusion before need. This approach was called the campaign methodology and the year 2000 was selected as the horizon year. Second repository opening was carefully placed to delay construction expenses as long as possible. Spent fuel received by the second repository during the initial five-year low receiving rate period left room for later spent fuel receipt at the first repository, thus delaying closing. In the high flow rate case the delay was one year while in the low flow rate case it was two years. In the high flow rate case the extra receiving capacity of the second repository also allowed earlier closing of AFR storage, thus creating some cost saving. This delay in first repository closing postpones the need for the high receiving rate mature phase of the second repository. This allows the desired delay in the second repository construction schedule.

This methodology does not consider whether a specific delivery of spent fuel does or does not use the second repository in deriving its price. This assumes that users of the second repository will be essentially the same as users of the first repository.

10.3 SCENARIO SUMMARY

Table 10-1 enumerates the case numbers assigned to scenario combinations and summarizes the principal inputs to the four cases of this study. Note that in the venture Cases 1 and 3, the receipts shown represent repository capacity, while the campaign Cases 2 and 4 both close in the year 2000.

Table 10-1. Scenario Summary

CASE NO.	1	2	3	4
Spent Fuel Delivery Rate	High	High	Low	Low
Closure Methodology	Venture	Campaign	Venture	Campaign
Receipts (MTU)	44,200	68,510	52,500	38,420
Closing Year	1997	2000	2003	2000

The detailed spent fuel flow for each case is seen in Tables 10-2 through 10-5, respectively. These flows show the result of combining the discharge data of Chapter 9 with the scenario assumptions above. Tables 10-2 and 10-3 show the five-year cooling delay high flow cases. These are identical through 1993. Note that the U.S. and foreign backlog was accepted from 1983 through 1987. In Case 2, the second repository opens in 1994, providing sufficient capacity to empty the AFRs over the next two years. The receiving rate of the first repository is then reduced to defer closing. This defers the need for the high receiving rate mature phase of the second repository which provides the desired delay in the start of second repository construction.

Tables 10-4 and 10-5 show the ten-year cooling low flow cases. They are identical through 2000. The acceptance of U.S. and foreign backlog was completed in 1991. Note that in 1990 U.S. and foreign candidate receipts exceeded capacity by 30 MTU (1.7 percent) requiring this amount to be deferred one year with no backlog accepted. Only the flow through 2000 was used

Table 10-2. Spent Fuel Flow - Case 1
Five-Year Delay, Venture Methodology
(Units: MTU)

YEAR	RECEIPTS			ALLOCATION					
	U.S.	FORGN	ACCUM	AT AFR		AT REPOSIT I		AT REPOSIT II	
				ANNUAL	ACCUM	ANNUAL	ACCUM	ANNUAL	ACCUM
1983	1230	770	2000	2000	2000	0	0	0	0
1984	1380	620	4000	2000	4000	0	0	0	0
1985	2610	410	7020	3000	7000	20	20	0	0
1986	2810	400	10230	1430	8430	1780	1800	0	0
1987	2860	400	13490	1480	9910	1780	3580	0	0
1988	1990	400	15880	610	10520	1780	5360	0	0
1989	2280	500	18660	1000	11520	1780	7140	0	0
1990	2620	500	21780	1340	12860	1780	8920	0	0
1991	3040	0	24820	-2280	10580	5320	14240	0	0
1992	3450	0	28270	-1870	8710	5320	19560	0	0
1993	3790	0	32060	-1530	7130	5320	24880	0	0
1994	4120	0	36180	-1200	5930	5320	30200	0	0
1995	4440	0	40620	-880	5100	5320	35520	0	0
1996	3580	0	44200	-1740	3360	5320	40840	0	0
1997	0	0	44200	-3360	0	3360	44200	0	0

FORGN: Foreign

ACCUM: Accumulated

REPOSIT: Repository

Table 10-3. Spent Fuel Flow - Case 2
Five-Year Delay, Campaign Methodology
(Units: MTU)

YEAR	RECEIPTS			ALLOCATION					
	U.S.	FORGN	ACCUM	AT AFR		AT REPOSIT I		AT REPOSIT II	
				ANNUAL	ACCUM	ANNUAL	ACCUM	ANNUAL	ACCUM
1983	1230	770	2000	2000	2000	0	0	0	0
1984	1380	620	4000	2000	4000	0	0	0	0
1985	2610	410	7020	3000	7000	20	20	0	0
1986	2810	400	10230	1430	8430	1780	1800	0	0
1987	2860	400	13490	1480	9910	1780	3580	0	0
1988	1990	400	15880	610	10520	1780	5360	0	0
1989	2280	500	18660	1000	11520	1780	7140	0	0
1990	2620	500	21780	1340	12860	1780	8920	0	0
1991	3040	0	24820	-2280	10580	5320	14240	0	0
1992	3450	0	28270	-1870	8710	5320	19560	0	0
1993	3790	0	32060	-1530	7180	5320	24880	0	0
1994	4120	0	36180	-4000	3180	5320	30200	2800	2800
1995	4440	0	40620	-3180	0	5320	35520	2300	5100
1996	4800	0	45420	0	0	3060	38580	1740	6840
1997	5170	0	50590	0	0	3060	41640	2110	8950
1998	5560	0	56150	0	0	2560	44200	3000	11950
1999	5970	0	62120	0	0	0	44200	5970	17920
2000	6390	0	68510	0	0	0	44200	6390	24310

FORGN: Foreign
ACCUM: Accumulated
REPOSIT: Repository

Table 10-4. Spent Fuel Flow - Case 3
Ten-Year Delay, Venture Methodology
(Units: MTU)

YEAR	RECEIPTS			ALLOCATION					
	U.S.	FORGN	ACCUM	AT AFR		AT REPOSIT I		AT REPOSIT II	
				ANNUAL	ACCUM	ANNUAL	ACCUM	ANNUAL	ACCUM
1982	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0
1985	20	0	20	0	0	20	20	0	0
1986	1180	600	1800	0	0	1780	1800	0	0
1987	1480	300	3580	0	0	1780	3580	0	0
1988	1580	200	5360	0	0	1780	5360	0	0
1989	1380	400	7140	0	0	1780	7140	0	0
1990	1480	300	8920	0	0	1780	8920	0	0
1991	1980	0	10900	0	0	1980	10900	0	0
1992	1790	0	12690	0	0	1790	12690	0	0
1993	1990	0	14680	0	0	1990	14680	0	0
1994	2280	0	16960	0	0	2280	16960	0	0
1995	2620	0	19580	0	0	2620	19580	0	0
1996	3040	0	22620	0	0	3040	22620	0	0
1997	3450	0	26070	0	0	3450	26070	0	0
1998	3790	0	29860	0	0	3790	29860	0	0
1999	4120	0	33980	0	0	4120	33980	0	0
2000	4440	0	38420	0	0	4440	38420	0	0
2001	4800	0	43220	0	0	4800	43220	0	0
2002	5170	0	48390	0	0	5170	48390	0	0
2003	4110	0	52500	0	0	4110	52500	0	0

FORGN: Foreign

ACCUM: Accumulated

REPOSIT: Repository

Table 10-5. Spent Fuel Flow - Case 4
Ten-Year Delay, Campaign Methodology
(Units: MTU)

YEAR	RECEIPTS			ALLOCATION					
	U.S.	FORGN	ACCUM	AT AFR		AT REPOSIT I		AT REPOSIT II	
				ANNUAL	ACCUM	ANNUAL	ACCUM	ANNUAL	ACCUM
1982	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0
1985	20	0	20	0	0	20	20	0	0
1986	1180	600	1800	0	0	1780	1800	0	0
1987	1480	300	3580	0	0	1780	3580	0	0
1988	1580	200	5360	0	0	1780	5360	0	0
1989	1380	400	7140	0	0	1780	7140	0	0
1990	1480	300	8920	0	0	1780	8920	0	0
1991	1980	0	10900	0	0	1980	10900	0	0
1992	1790	0	12690	0	0	1790	12690	0	0
1993	1990	0	14680	0	0	1990	14680	0	0
1994	2280	0	16960	0	0	2280	16960	0	0
1995	2620	0	19580	0	0	2620	19580	0	0
1996	3040	0	22620	0	0	3040	22620	0	0
1997	3450	0	26070	0	0	3450	26070	0	0
1998	3790	0	29860	0	0	3790	29860	0	0
1999	4120	0	33980	0	0	4120	33980	0	0
2000	4440	0	38420	0	0	4440	38420	0	0
2001	4800	0	43220	0	0	1800	40220	3000	3000
2002	5170	0	48390	0	0	2170	42390	3000	6000
2003	5560	0	53950	0	0	2560	44950	3000	9000
2004	5970	0	59920	0	0	2970	47920	3000	12000
2005	6390	0	66310	0	0	4580	52500	1810	13810

FORGN: Foreign
ACCUM: Accumulated
REPOSIT: Repository

in Case 4. The entire flow through first repository closing in 2005 is shown in Table 10-5 to illustrate the required process of establishing the impact of the initial phase in order to place the start of capital construction.

Each case priced in this study has unique strengths supporting its reasonable use as a baseline. High flow cases (1 & 2) illustrate inclusion of AFR and transportation cost centers. Low flow cases (3 & 4) show the impact of lower deferred revenues. The venture methodology, as applied in Cases 1 and 3, minimizes assumptions and therefore is based on the most supportable data. The campaign methodology, as applied in Cases 2 and 4, presents a formulation which can be used continuously through any eventuality. Therefore, the results will represent broadly based variations carefully constructed to present prices representing a range of views of the spent fuel management program.

11.0 PRICING METHODOLOGY

This chapter discusses the methodology used by this study to derive the price of spent fuel management from the costs and spent fuel flows described in earlier chapters. Complete lists of equations used, variable meanings, and parameter values will be found in Appendix C.

11.1 PRICING CONSTRAINTS

The basic spent fuel pricing constraint of the entire analysis is:

- The discounted value of all relevant government costs must be exactly recovered by the discounted value of all applicable revenues received over the life of the program. An equivalent statement would be that the present value (PV) of all costs must equal the PV of all revenues.

Another important constraint is that:

- Price is imposed on a one-time basis only. That is, once a fee has been established for a particular shipment, there will be no retroactive adjustments.

But it should be noted that an adjustment of prices might occur if spent fuel were to be retrieved and reprocessed. However, in this analysis, such a possibility is not considered and no credits for the Pu and U²³⁵ values in the spent fuel are included.

Another constraint is that:

- The costs of post operational surveillance of the buried material, starting at the time that the final repository of the spent fuel is decommissioned, must be included in the price.

Finally, a requirement of the analysis was that:

- The components of price associated with the various cost centers have to be calculated and published along with the total price.

In connection with the above requirement, it must be emphasized that there is no necessary connection between the cost directly generated at a cost center by a particular shipment and the value of the price component allocated to that shipment. This point will be explained more fully in paragraph 11.3.

11.2 PRICING ASSUMPTIONS

The following assumptions were used in deriving the price methodology.

Where appropriate, rationale and/or comments on the assumptions are presented.

1. Price components correspond to the following cost centers which were identified in reference XI-1 and shown in Table 11-1.

Table 11-1. Spent Fuel Management Cost Centers

Cost Center	Comment
1. Away From Reactor (AFR) storage	In certain cases, an AFR will not be needed. But complete formulas for AFR pricing are given.
2. Encapsulation facility	May be colocated with repositories.
3. Geologic repository	This cost center includes perpetual surveillance costs.
4. Transportation	Only government costs included.
5. Research & Development (R&D)	Government funded R&D only.
6. Government overhead	Includes costs of government personnel associated with program, but not located at sites.

2. The pricing algorithms, except as specifically noted, follow as closely as possible the methodology used by DOE to price uranium enrichment separative work units (SWU). This ground rule was established by OWI at a meeting at Germantown, Md. on December 13, 1977. The rationale is that use of the SWU procedures would be compatible with provisions of the Atomic Energy Act of 1954, as amended in 1973, which requires recovery of government cost, including imputed interest and depreciation charges (reference XI-2).
3. The time horizon for the pricing formulas extends from the base year, 1978, to the end year of the scenario. However, there are provisions for recovery of any undepreciated government capital still on the books at the end of the scenario.

Undepreciated book value is determined as follows. All government capital is assumed to be completely depreciated after ten or more years of beneficial use. If capital is beneficially used for less than ten years, depreciation is calculated by the straight-line method assuming a ten-year depreciation life. There is no salvage value for either government or privately owned facilities. The above assumptions were established by DOE/OWI at a meeting held at Oak Ridge, Tennessee on December 2, 1977.

4. All calculations for establishment of the initial price are in terms of constant 1978 dollars. Such an assumption is compatible with an option to recompute prices.
5. All incremental government costs (capital as well as operating) are recognized for discounting purposes in the year incurred. The above procedure is equivalent to recapture of government inputted interest and depreciation charges as required by the Atomic Energy Act of 1954. A proof of the equivalence of the two methods is given in Appendix D of this report.
6. All government revenues are recognized for discounting purposes in the year that spent fuel is first received at a designated site. Title to the spent fuel is assumed to be transferred to the government at the point of first receipt.
7. In addition to incremental costs, one category of sunk costs is recognized which pertains to spent fuel storage R&D performed before 1978. These costs are all recognized in the base year of 1978. The rationale for inclusion of sunk costs is that such costs must be recovered to be consistent with the basic constraint of the pricing analysis. However, if the algorithms developed are ever used for system evaluations, only marginal costs should be considered.

8. For purposes of discounting, costs and revenues are assumed to be generated at the beginning of each time period while interest charges are assumed to be due and payable at the end of each period. Further, beneficial use of a facility is assumed to continue for one full period after the last charge (other than interest) for a facility is incurred.
9. Post operational activities at various facilities are handled by an annuity or trust fund as follows:
  - a. Post operational costs for repository sites are covered by an annuity which will provide required annual funding to keep the repository in an operating mode in perpetuity. The annuity is purchased either in the last year of site operation or the last year of the time horizon (whichever comes first). The cost of the annuity is recognized in the year of purchase for purposes of discounting. Funds are made available by withdrawal of simple interest earned by the annuity at the same rate as that assumed for government interest.
  - b. Decommissioning costs are covered by recognizing the PV of these costs in the last operational year of a site. In the repositories, seven years of post operational decommissioning costs are present valued while three years of decommissioning costs are included in the costs of the last year of AFR operations. The values of these costs will be found in earlier chapters.
10. The discount rate for costs and revenues and the imputed government interest rate are assumed to be the same as they are in the SWU pricing formulas.
11. All AFR sites are assumed to be privately owned and operated by unregulated corporations. It is assumed that the private owner would bill the government for an amount which would cover operations costs and capital recovery charges. Payments to the AFR owners would be a government cost recognized as incurred.

If the AFR were government owned, the procedures used to calculate the PV of encapsulation costs would be applicable to the AFR. If the AFR were utility owned, all AFR formulas developed would apply. Also, all parameter values, except for the return rate, would be the same. (The utilities cost of capital would be the return rate.)

11.3 PROCEDURES

11.3.1 General Procedures

The basic formula for calculation of the initial price is derived as follows.

From the basic constraint, the PV of government costs must equal the PV of government revenues. If C_t is government costs incurred in the t -th year, R_t is revenue received in the t -th year, b is the base year (1978) and S_z the last year of scenario "z", the constraint equation is:

$$\sum_{t=y-b}^{S_z-b} \frac{C_t}{(1+d)^t} = \sum_{t=y-b}^{S_z-b} \frac{R_t}{(1+d)^t} \quad (1)$$

where $y = 1973, 1979, \dots, S_z$ and d is the discount rate.

In the methodology adopted, the price "P" is invariant over time while the quantity of spent fuel received in the t -th year (Q_t) does vary with time. Since revenue is price times quantity, Equation (1) may be written as:

$$\sum_{t=y-b}^{S_z-b} \frac{C_t}{(1+d)^t} = \sum_{t=y-b}^{S_z-b} \frac{PQ_t}{(1+d)^t} \text{ or } P = \frac{\sum_{t=y-b}^{S_z-b} \frac{C_t}{(1+d)^t}}{\sum_{t=y-b}^{S_z-b} \frac{Q_t}{(1+d)^t}} \quad (2)$$

The price component (P_i) associated with the i -th cost center ($i=1, 2, \dots, 8$) is defined as

$$P_i = \frac{\sum_{t=y-b}^{S_z-b} \frac{C_{it}}{(1+d)^t}}{\sum_{t=y-b}^{S_z-b} \frac{Q_t}{(1+d)^t}}$$

where C_{it} is the cost incurred at the i -th cost center in the t -th year.

Note that there is no attempt to associate a particular shipment with a particular cost center. That is, every shipment has to bear a share of all costs regardless of whether that shipment utilizes the services of any particular cost center. For example, spent fuel sent directly to a repository (thus bypassing an AFR) would still bear its share of AFR costs. Further, the price of a shipment received in the last year of a time horizon would reflect the effect of capital and

operating costs incurred in all the previous years. Accordingly, the price component calculated does not necessarily correspond to services rendered.

11.3.2 Procedures for Government Owned or Directly Funded Cost Centers

As indicated in Paragraph 11.2, all costs for the categories identified above are recognized as incurred and discounted accordingly to obtain the PV of a cost center. But there also may be a closing credit (negative cost) for undepreciated capital or a closing charge for purchase of trust funds. The formulas used for each cost center are presented in Appendix C. Note that all cost centers are assumed to be either government owned or directly funded by the government, except for the AFRs, which are indirectly funded as indicated below.

11.3.3 Procedures for Costs of Privately Owned Cost Center (AFR)

It is assumed that the government will indirectly fund a privately owned cost center by periodic payments to the owners.

Operating and maintenance (O&M) costs are assumed to be billed to the government on a dollar for dollar basis. The AFR O&M costs then become a cost to the government. There are no management fees,¹ since the private operator is assumed to earn profits in the form of return on capital. The problem then is to formulate a procedure for calculating a schedule of government payments which would enable the private owner to profitably recover his capital investment in an AFR.

The approach adopted was to require that the discounted sum of a series of fixed annual payments over the life of the AFR equals the PV of an AFR investment. Note that no AFR capital investments after start of AFR operations are required. The imputed interest rate used to calculate the PV of the AFR investment was the after tax return rate on the investment. The PV of the investment was then reduced by amounts corresponding to the PV of:

- Investment tax credits (ITC)
- Accelerated depreciation tax benefits.

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¹ In the case of a government owned, contractor operated AFR, there would be a management fee, but there would be no private capital charges.

In these calculations, it was assumed that the AFR venture was a subsidiary of a corporation which could fully utilize all income tax credits and that benefits flowed through the parent corporation.

Using the notation and cost center designation, l , presented on the previous page:

$$\text{Adjusted PV}(C_l) = \text{PV}(R_l) = \sum_{t=1}^n \frac{R_{lt}}{(1+k)^t} \quad (4)$$

where k = private after tax discounted cash flow (DCF) return rate and n = operating life of AFR.

By hypothesis, there is a level stream of revenues ($\bar{R}_l$) to cover capital costs. Accordingly,

$$\text{Adjusted PV}(C_l) = \bar{R}_l \sum_{t=1}^n \frac{1}{(1+k)^t} \quad \text{or} \quad \bar{R}_l = \left(\sum_{t=1}^n \frac{1}{(1+k)^t} \right)^{-1} (\text{Adjusted PV}(C_l)) \quad (5)$$

The inverse of the summation is a function only of k and n and is called the capital recovery factor or

$$\text{CRF}(k,n) = \frac{k(1+k)^n}{(1+k)^{n+1} - 1}$$

The problem then becomes one of developing a formula for the adjusted PV of the AFR investment. The approach was to divide the investment into two parts, namely:

- Depreciable investment (capital equipment and buildings)
- Non-depreciable investment (land and working capital).

If depreciable investment costs in the t -th year are designated as K_{lt} , the PV of depreciable investment (using the first year of beneficial use, B_l , as the base year) is equal to:

$$\sum_{t=B_l}^{B_l+b} \frac{K_{lt}}{(1+k)^{t-B_l+b}} = \text{PV}(K_l) \quad \text{where } y \text{ and } b \text{ are as before}$$

Note in the algorithms (Appendix C) that provision is made for further subscripting to allow for the presence of more than one facility.

The PV of depreciable investments is then adjusted for the two tax benefits and the present value of property tax and insurance premiums on the value of depreciable capital. Derivations of the three adjustments follow:

a. Derivation of ITC Corrections

The tax credit law is such that a fraction, α , of depreciable capital can be taken as a credit as capital costs are incurred. Therefore, the PV of the credit is

$$\sum_{t=y-b}^{B_1-b} \frac{\alpha K_1 t}{(1+k)^{t-B_1-b}} \quad (6)$$

which is simply equal to α times the PV of depreciable capital.

b. Derivation of Depreciation Correction

Since depreciation is a book charge against taxable profits but not cash flow, the net benefits as a fraction of depreciable capital is multiplied by τ , the effective federal and state income tax rate to determine the cash value of the benefit. Three modes (M) of depreciation are permitted by the IRS, all of which are included in the formulas for $D(M)$, the depreciation factor (see Appendix C). However, unless otherwise specified, the double-the-declining balance method is used.

In this mode ($M=3$), twice the straight line rate ($\frac{1}{n}$) is applicable to undepreciated capital. That is, the value of the tax credits are $2\tau/n$, $2\tau/n(1-2/n)$, $2\tau/n(1-2/n)^2 \dots$ times the PV of depreciable capital. Since the benefits are received over the life of the AFR, the annual benefits must be present valued to derive the PV of the depreciation factor. Thus,

$$D(M) = 2/n \sum_{t=0}^{n-1} \frac{(1-2/n)^t}{(1+k)^t} = \frac{2(1+k)}{n(k+2/n)} \quad (7)$$

for the double-declining mode.

c. Derivation of Property Tax and Insurance (Ad Valorem) Factor

The so called ad valorem charges may either be treated as an operating expense or as a capital charge. The rationale for the latter treatment is that property tax and insurance premiums can be expressed as decimal fractions (β_1 and β_2) of the PV of undepreciated capital. Since these charges are tax deductible, the PV of the factor (that multiplies the PV of depreciable capital) is

$$\sum_{t=1}^n \frac{(1-\tau)(\beta_1+\beta_2)}{(1+k)^t} = \frac{(1-\tau)(\beta_1+\beta_2)}{\text{CRF}(k,n)} \quad (8)$$

Finally, recall that all returns to capital are subject to income taxes at rate τ . Therefore, $\tau \bar{R}_{1k}$ (returns to depreciable capital) is subtracted from $\bar{R}_{1k}$ the before-tax required revenue. Accordingly, substituting in (5) we have

$$\bar{R}_{1k} - \bar{R}_{1k}\tau = \text{CRF}(k,n) \text{ Adj PV}(K_1) \text{ or } \bar{R}_{1k} = \frac{\text{CRF}(k,n)}{(1-\tau)} \text{ Adj PV}(K_1) \quad (9)$$

Then substituting factors 6, 7, and 8 derived above, the required revenue to recover depreciable AFR capital is:

$$\bar{R}_{1k} = \text{PV}(K_1) \frac{\text{CRF}(k,n)}{(1-\tau)} \left[1 - \alpha - \frac{2\tau(1+k)}{n(k+2/n)} + \frac{(1-\tau)(\beta_1+\beta_2)}{\text{CRF}(k,n)} \right] \quad (10)$$

Two aspects of Equation (1) should be noted as follows:

- Receipt of an ITC does not decrease a depreciation base, hence the depreciation base is not multiplied by $1-\alpha$.
- When the indicated multiplications are made, the ad valorem factor $(\beta_1+\beta_2)$ simply multiplies the PV of depreciable capital.

Non-depreciable capital is handled in a manner similar to depreciable capital. The PV of non-depreciable capital is the PV of land payments (the formula has the same form as for depreciable capital) plus working capital. No return on working capital prior to operations is required since the working capital investment can be deferred until just before operations start.

The PV of land and working capital is then reduced by the factor $\left[1 - \frac{1}{(1+k)^n}\right]$ to reflect resale of land and recovery of working capital at the

end of operations. The adjusted PV is then multiplied by $\frac{CRF(k,n)}{(1-\tau)}$ to calculate the revenue required to recover land and working capital investments at the after tax rate of k. (Note that the property tax on land is included in O&M costs).

It is possible that working capital for the AFR will not be an explicit output of the cost model. Accordingly, a procedure for estimating AFR working capital is described below.

Working capital is defined by accountants as:

- Cash equivalent investments, plus inventory, plus accounts receivable, minus accounts payable.

Since AFR cash investments will probably be negligible and since the spent fuel inventory has no value, working capital can be redefined as receivables minus trade accounts payable. Since operating materials costs are expected to be very low in the AFR, a rough estimate of AFR working capital can be obtained by consideration only of accounts receivable.

To estimate receivables, it was assumed that the government would be billed for O&M wages and salaries and capital charge remittances to the parent corporation. The O&M costs are available from the cost model while an estimate of capital charges (without returns to working capital) can be made using the formulas presented above. The working capital requirement then would be:

$$(\text{Required annual revenue}) \frac{(\text{Government paytime in months})}{12}$$

For purposes of the initial price estimates, a one-month delay between billings to the government and receipt of payments from the government was assumed.

Unless otherwise specified, all calculations are based on use of the parameters shown in Table 11-2.

Table 11-2. Pricing Parameter Values

Parameter	Value	Comments
Discount rate and government interest rate.	.065	Average cost of U.S. debt currently used in SWU discounting calculations.
Private unregulated after-tax AFR return rate.	0.12	Per 12/2/77 Oak Ridge meeting. Typical return is 0.15, but AFR has no market risk. Use 0.08 (utility cost of capital) if AFR utility owned.
Effective income tax rate.	0.50	Based on .48 federal and .04 state rate, i.e., $.48 + .52(.04) = .50$.
Effective ITC.	0.06	Based on nominal .10 rate for equipment corrected for the 60% equipment content of an AFR.
Equipment and building property tax rate.	0.015	Typical value.
Equipment and building insurance rate.	0.005	Typical value.

12.0 RESULTS

This chapter presents the results of using the costs described in Chapters 3 through 8, and the spent fuel flow scenarios described in Chapters 9 and 10, as input to the spent fuel management pricing methodology described in Chapter 11. The components of price are displayed and discussed by cost center and the components of undiscounted cost are displayed and discussed by cost center and by category. Finally, some general comparisons and interpretations are presented to put the results in perspective.

12.1 RESULTS PRESENTATION

Table 12-1 summarizes the one-time price of spent fuel management derived for each of the four cases defined in Chapter 10 of this study.

TABLE 12-1. Summary of Price Results

	Case 1 High Venture	Case 2 High Campaign	Case 3 Low Venture	Case 4 Low Campaign
\$/KGU ¹	152.5	134.3	116.1	134.1
Mills/kW hr.	.713	.628	.543	.627
Cost (Undiscounted 1978 \$ B)	6.290	7.539	4.093	3.394

¹ Kilograms of uranium charged initially to the reactor.

The mills per kilowatt-hour shown on this chart were derived by multiplying the price in dollars per kilogram of uranium by a linear factor derived from the reactor characteristics of reference IX-1. Examination of Table 12-1 shows that the prices vary only ± 13 percent from their mid-range value. Furthermore, the effect of the timing of received fuel is evident from the fact that both the high and low extremes of price and cost occur in separate cases. The coincidence of Case 2 and Case 4 (difference 0.2 percent) illustrates high AFR expenses early to handle high flow quantities compensating for fewer later revenues with low flow quantities.

Figure 12-1 presents the cost center components of the price results in dollars per kilogram of uranium. The values of these components can be found in Appendix B. This figure shows clearly that the AFR and the transportation cost centers of Cases 1 and 2 increase the price up to and past the values of the other cost centers in Cases 3 and 4. Note especially that the difference between Case 1 and Case 2 is almost completely made up of the AFR cost center difference. This cost difference arose from two factors; first, the availability of the second repository's receiving capacity which allowed emptying of the AFRs two years earlier in Case 2, and second, the greater total receipts in Case 2 of which most do not enter an AFR.

Figure 12-1 illustrates the impact of spent fuel flow quantity and timing by highlighting the increased proportion represented by the early, fixed, costs of Research and Development on Cases 3 and 4 over Cases 1 and 2. Specifically, the fixed total R&D costs are spread over more kilograms of spent fuel, thus resulting in lower dollars per kilogram. The increased geologic repository contribution to Case 4 over Case 3 further illustrates flow impact because the undiscounted cost center total for Case 4 is 30 percent less than for Case 3.

In order to explore the minimum price derivable from the ground rules of this study, two additional cases were calculated in which fuel was delivered to the repository at precisely the design receiving rate without AFR storage for both the venture and campaign methodologies. This receiving scenario led to an average age of fuel at placement of approximately 6 years which allowed increase of first repository capacity to 46,160 MTU. Careful phase-in of the second repository in the campaign case delayed the first repository closing two years and emplaced a total of 66,920 MTU. The results of these calculations are shown in Figures 12-2 and 12-3 for the venture and campaign methodologies respectively. Note that the geologic repository, encapsulation, R&D, and government overhead cost centers increase in both design rate cases over high flow cases, but the elimination of AFR and transportation components leads to the minimum price for this study's ground rules.

Table 12-2 shows the life cycle undiscounted cost breakdown of the four cases by cost center. All applicable categories of cost are

Figure 12-1. Cost Center Components of Price Results

Figure 12-2. Venture Methodology Cases

Figure 12-3. Campaign Methodology Cases

included in each cost center's expense. This table illustrates that the dominant cost centers are the geologic repository and AFR storage which constitute between 64 and 74 percent of total cost. Details of all values shown can be found in Appendix A. Total AFR storage costs to the government are included only in Table A-6 and A-7 of Appendix A because of the required translation from cost to the private operator.

TABLE 12-2. Life Cycle Cost Summary By Cost Center
(Undiscounted 1978 \$M)

	1 High Venture	2 High Campaign	3 Low Venture	4 Low Campaign
Geologic Repository	2309	3475	2755	2167
Encapsulation	511	824	544	472
AFR	2298	2029	0	0
Transportation	417	417	0	0
R&D	560	560	560	560
Government Overhead	195	234	234	195
Total	6290	7539	4093	3394

Table 12-3 presents the life cycle cost summary for each case by cost category. This table shows that the dominant cost category changes from capital cost in Cases 1 and 2 to O&M cost in Cases 3 and 4. The category "Other" contains the sum of transportation, R&D, and government overhead costs. Note that although trust fund costs constitute between 8 and 13 percent of undiscounted cost, their very late occurrence constitutes only 3.5 to 5.5 percent of the price of spent fuel management. Detailed cross references of cost center to category cost for each case will be found in Appendix A.

TABLE 12-3. Life Cycle Cost Summary By Category

(Undiscounted 1978 \$M)

	1 High Venture	2 High Campaign	3 Low Venture	4 Low Campaign
Capital	2980	3354	886	886
O&M	1560	2327	1879	1485
Trust Funds	578	647	534	268
Other	1172	1211	794	755
Total	6290	7539	4093	3394

12.2 PRICE INTERPRETATIONS

Figure 12-4 illustrates the comparison of Case 2 price to those of other nuclear fuel cycle components as estimated in reference XII-1. Prices illustrated represent average 1985 values of a 1200 MWe PWR with startup in 1982, in 1976 dollars. The spent fuel management charge falls below the average of these costs but above the lowest value. Therefore, the spent fuel management price is comparable to those of other fuel cycle components. It is, however, an additional cost component which increases the total fuel cycle price. A number of conservative assumptions have been included, contingency funds have been provided, and the system parameters, although reasonable, are not optimized. Therefore, the absolute level of the spent fuel management prices presented in this study are defensible as accurate within the estimate error of the cost estimates (maximum $\pm$ 30 percent).

The sensitivity of these prices is quite low, only $\pm$ 13 percent from their mid-range value even though costs vary $\pm$ 38 percent, and receipts $\pm$ 28 percent from their mid-range value. This insensitivity results from compensating factors which return prices to the observed

¹Includes AFR operator return, taxes, and insurance.

Figure 12-4. Spent Fuel Management Cost Comparison

range. These include additional cost centers (AFR and Transportation) for high early receipts versus less revenues for low receipts. Even the optimum flow of spent fuel price has been shown to be only 24 percent below the four case mid-range value.

Several additional topical concerns which could not be investigated within the resources of this study may cause more sensitivity in price than observed here. These include:

- Other media besides salt which impacts capital cost and capacity of the repository.
- First repository start date which impacts the quantity of AFR storage required and, therefore, AFR charges to the government.
- Government ownership of AFR storage which reduces costs because of the different cost recovery methodologies.
- Long term AFR utilization which allows accepting additional fuel at minimum cost.
- Cask flow constraints which delay AFR closing and transportation costs.
- Government cask ownership which reduces transportation cost because of the different cost recovery methodologies.
- Second repository start date considerations.
- Methods to recompute price in the presence of changes.
- Additional parametric variations such as capital cost, capacity, and design receipt rate may show additional sensitivity highlights of interest.
- Less than indefinite retrievability which reduces O&M costs and increases repository capacity.

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APPENDIX A. DETAILED COST RESULTS

This Appendix presents the detailed undiscounted costs for each case examined in this study. The assumptions and data sources which support these data are enumerated in the body of this report.

Table A-1 summarizes the major inputs and outputs of all four cases including discounted values. Note especially the impact of timing shown by the relationships of undiscounted range of variation to discounted range of variation in both the costs and the receipts.

Tables A-2 through 5 show the detailed costs by year for all elements of the four study cases. Note that these costs do not add to the undiscounted costs shown in Table A-1 in Cases 1 and 2 because they exclude AFR operator's return, taxes, and insurance.

Tables A-6 through A-9 show the cross reference of cost center to cost category expenditures for the four cases. From these values are those of Tables A-2 and A-3, undiscounted AFR operator's return, taxes, and insurance (included in Tables A-6 and A-7) can be calculated to be \$1526 M (1978) in Case 1 and \$1280 M (1978) in Case 2. Capital cost totals in all tables involving Cases 2 and 4 include ending undepreciated value of still available facilities.

Table A-10 displays the contingency funds provided in each case. Both capital and post operation contingencies are included. No additional contingency has been added after the present value calculation in contrast to the final 15 percent contingency included in uranium enrichment price calculation.

Table A-11 displays the annual capitalization charges resulting from Chapter 11 methodology applied to each AFR. Note that although the charge increases for shorter life spans, the increase is not large enough to result in greater total charges to the government for less active life.

TABLE A-1. DETAILED DATA SUMMARY

CASE NO. FLOW RATE CLOSING METHOD	1 HIGH VENTURE	2 HIGH CAMPAIGN	3 LOW VENTURE	4 LOW CAMPAIGN
PRICE \$/KGU ¹ MILLS/KWHR ²	152.5 .7132	134.3 .6279	116.1 .5430	134.1 .6270
COST (\$B) UNDISCOUNTED 1978 DISCOUNTED	6.290 3.220	7.539 3.738	4.093 2.011	3.394 1.904
RECEIPT (MTU) ¹ UNDISCOUNTED DISCOUNTED	44,200 21,114	68,510 27,837	52,500 17,317	38,420 14,197
CLOSING YEAR FIRST REPOSITORY SECOND REPOSITORY SCENARIO	1997 N/A 1997	1998 2011 2000	2003 N/A 2003	2005 2022 2000

¹ Initially charged to the reactor.

² Linear multiple of \$/KGU using Reference IX-1 factors.

**TABLE A-2. DETAILED COST INPUTS – CASE 1
HIGH FLOW RATE, VENTURE METHODOLOGY
1978 \$ M**

YEAR CATEGORY	TOTAL	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	ENDING VALUE
SPENT FUEL FLOW																												
ANNUAL RECEIPTS	44200						2000	2000	3020	3210	3260	2390	2780	3120	3040	3450	3790	4120	4440	3580	0							
ACCUMULATION	N/A						2000	4000	7020	10230	13490	15880	18660	21780	24820	28270	32060	36180	40620	44200	44200							
AFR CONTENTS	12860						2000	4000	7000	8430	9910	10520	11520	12860	10580	8710	7190	5980	5100	3360	0							
AFR SHIPMENTS	12860														2280	1870	1530	1200	880	1740	3360							
COSTS																												
RESEARCH & DEVELOPMENT BEFORE 78	(560.0)																											
ANNUAL R&D	40.1 519.9	86.1	120.1	97.8	93.4	76.1	27.5	9.4	5.8	3.7																		
GOVERNMENT OVERHEAD	195.						13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0							
TRANSPORTATION	417.155														73.96	60.66	49.63	38.926	28.545	56.442	108.992							
ENCAPSULATION	(508.98)																											
#1 CAPITAL	287.6				20.6	65.7	87.4	92.1	21.8																			
OPS. & MAINT.	201.44								.09	8.53	8.53	8.53	8.53	8.53	23.02	23.02	23.02	23.02	23.02	23.02	20.58							
DECOMMISSIONING	19.94																				19.94							
#2 CAPITAL																												
OPS. & MAINT.																												
DECOMMISSIONING																												
GEOLOGIC REPOSITORY	(2309.153)																											
#1 CAPITAL	596.0	0.35	2.68	22.68	90.77	146.9	132.86	104.95	94.81																			
OPS. & MAINT.	1199.208								.77	77.2	78.14	78.4	77.64	78.08	127.02	120.14	112.27	113.78	125.87	116.548	93.35							
DECOMMISSIONING	156.56																				156.56							
POST OPS.	357.385																				357.385							
#2 CAPITAL																												
OPS. & MAINT.																												
DECOMMISSIONING																												
POST OPS.																												
AFR STORAGE ¹	(780.67)																											
#1 CAPITAL	273.		15.	34.	111.	113.																						
LAND	5.		3.	2.																								
WORKING CAPITAL	6.19						6.19																					
OPS. & MAINT.	82.						6	6	6	6	4	4	4	4	6	6	6	6	6	6	6							
DECOMMISSIONING	22.07																				22.07							
#2 CAPITAL	273.				15	34	111.	113																				
LAND	5.				3	2																						
WORKING CAPITAL	6.34								6.34																			
OPS. & MAINT.	78.								6	6	6	6	6	6	6	6	6	6	6	6	6							
DECOMMISSIONING	22.07								6												22.07							

¹ AFR Operator's Cost – Excludes Return, Taxes, and Insurance.

**TABLE A-3. DETAILED COST INPUTS – CASE 2
HIGH FLOW RATE, CAMPAIGN METHODOLOGY
1978 \$ M**

YEAR CATEGORY	TOTAL	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	ENDING VALUE
SPENT FUEL FLOW																												
ANNUAL RECEIPTS	68510						2000	2000	3020	3210	3260	2390	2780	3120	3040	3450	3790	4120	4440	4800	5170	5560	5970	6390				
ACCUMULATION	N/A						2000	4000	7020	10230	13490	15880	18660	21780	24820	28270	32060	36180	40620	45420	50590	56150	62120	68510				
AFR CONTENTS	12860						2000	4000	7000	8430	9910	10520	11520	12860	10580	8710	7180	3180	0									
AFR SHIPMENTS	12860														2280	1870	1530	4000	3180									
COSTS																												
RESEARCH & DEVELOPMENT BEFORE 78	(560.0)																											
ANNUAL R&D	40.1 519.9	86.1	120.1	97.8	93.4	76.1	27.5	9.4	5.8	3.7																		
GOVERNMENT OVERHEAD	234.						13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0				
TRANSPORTATION	417.15														73.96	60.66	49.63	129.75	103.15									
ENCAPSULATION	(819.822)																											
#1 CAPITAL	287.6				20.6	65.7	87.4	92.1	21.8																			
OPS. & MAINT.	195.94								.09	8.53	8.53	8.53	8.53	8.53	23.02	23.02	23.02	23.02	23.02	13.46	13.46	11.18						
DECOMMISSIONING	19.94																					19.94						
#2 CAPITAL	200.72												20.6	65.7	87.4	92.1	21.8											
OPS. & MAINT.	113.04																	13.16	12.52	11.85	12.27	13.42	23.81	26.01				
DECOMMISSIONING	2.582																						2.582				86.88	
GEOLOGIC REPOSITORY	(3475.109)																											
#1 CAPITAL	596.0	0.35	2.68	22.68	90.77	146.9	132.86	104.95	94.81																			
OPS. & MAINT.	1265.839								.77	77.2	78.14	78.4	77.64	78.08	127.02	120.14	112.27	113.78	125.07	92.931	90.089	93.509						
DECOMMISSIONING	156.56																					150.50						
POST OPS.	357.385																					357.385						
#2 CAPITAL	417.2									.35	2.68	22.68	90.77	146.9	132.86	104.95	94.81											
OPS. & MAINT.	615.582																	93.541	87.05	78.329	82.438	95.428	92.292	86.504				
DECOMMISSIONING	20.26																							20.26				
POST OPS.	46.283																							46.283				
AFR STORAGE ¹	(749.06)																											
#1 CAPITAL	273.		15.	34.	111.	113.																						
LAND	5.		3.	2.																								
WORKING CAPITAL	6.34						6.34																					
OPS. & MAINT.	70.						6	6	6	6	4	4	4	4	6	6	6	6	6									
DECOMMISSIONING	22.07																											
#2 CAPITAL	273.				15.	34.	111.	113.																				
LAND	5.				3	2																						
WORKING CAPITAL	6.58								6.58																			
OPS. & MAINT.	88								6	6	6	6	6	6	6	6	6	6	6									
DECOMMISSIONING	22.07																											

¹ AFR Operator's Cost – Excludes Return, Taxes, and Insurance.

TABLE A-4. DETAILED COST INPUTS – CASE 3
LOW FLOW RATE – VENTURE METHODOLOGY
1978 \$ M

YEAR CATEGORY	TOTAL	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	ENDING VALUE
SPENT FUEL FLOW ANNUAL RECEIPTS ACCUMULATION AFR CONTENTS AFR SHIPMENTS	52500 N/A								20 20	1780 1800	1780 3580	1780 5360	1780 7140	1780 8920	1980 10900	1790 12690	1990 14680	2280 16960	2620 19580	3040 22620	3450 26070	3790 29860	4120 33980	4440 38420	4800 43220	5170 48390	4110 52500	
COSTS RESEARCH & DEVELOPMENT BEFORE 78 ANNUAL R&D	(560.0) 40.1 519.9																											
GOVERNMENT OVERHEAD	234.									13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	
TRANSPORTATION																												
ENCAPSULATION #1 CAPITAL OPS. & MAINT. DECOMMISSIONING #2 CAPITAL OPS. & MAINT. DECOMMISSIONING	(541.48) 287.6 234.44 19.94				20.6	65.7	87.4	92.1	21.8 .09	8.53	8.53	8.53	8.53	8.53	8.78	8.54	8.79	10.83	11.25	13.45	15.64	16.07	18.16	18.55	20.68	21.14	19.82 19.94	
GEOLOGIC REPOSITORY #1 CAPITAL OPS. & MAINT. DECOMMISSIONING POST OPS. #2 CAPITAL OPS. & MAINT. DECOMMISSIONING POST OPS.	(2754.832) 596.0 1644.887 156.56 357.385	0.35	2.68	22.68	90.77	146.9	132.86	104.95	94.81 .77	77.2	78.14	78.4	77.64	78.08	88.54	79.18	73.95	79.35	96.29	92.59	94.20	108.46	104.61	105.84	112.567	113.76	105.32 156.56 357.385	
AFR STORAGE #1 CAPITAL LAND WORKING CAPITAL OPS. & MAINT. DECOMMISSIONING #2 CAPITAL LAND WORKING CAPITAL OPS. & MAINT. DECOMMISSIONING																												

TABLE A-5. DETAILED COST INPUT – CASE 4
LOW FLOW RATE CAMPAIGN METHODOLOGY
1978 \$ M

YEAR CATEGORY	TOTAL	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	ENDING VALUE
SPENT FUEL FLOW																												
ANNUAL RECEIPTS	38420								20	1780	1780	1780	1780	1780	1980	1790	1990	2280	2620	3040	3450	3790	4120	4440				
ACCUMULATION	N/A								20	1800	3580	5360	7140	8920	10900	12690	14680	16960	19580	22620	26070	29860	33980	38420				
AFR CONTENTS																												
AFR SHIPMENTS																												
COSTS																												
RESEARCH & DEVELOPMENT BEFORE 78	(560.0)																											
ANNUAL R&D	40.1																											
	519.9	86.1	120.1	97.8	93.4	76.1	27.5	9.4	6.8	3.7																		
GOVERNMENT OVERHEAD	195.									13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0				
TRANSPORTATION																												
ENCAPSULATION	(410.34)																											
#1 CAPITAL	287.6				20.6	65.7	87.4	92.1	21.8																			
OPS. & MAINT.	112.74								.09	8.53	8.53	8.53	8.53	8.53	8.78	8.64	8.79	10.83	11.25	13.45	15.64	16.07	18.16	18.55				
DECOMMISSIONING	10.00																							10.00				
#2 CAPITAL	0 ¹																			20.6	65.7	87.4	92.1	21.8			287.6	
OPS. & MAINT.																												
DECOMMISSIONING																												
GEOLOGIC REPOSITORY	(2166.911)																											
#1 CAPITAL	596.0	0.35	2.68	22.68	90.77	146.9	132.86	104.95	94.81																			
OPS. & MAINT.	1313.21								.77	77.2	70.14	78.4	77.84	78.08	88.54	79.18	73.95	79.35	96.29	92.59	94.20	108.46	104.61	105.84				
DECOMMISSIONING	78.46																							78.46				
POST OPS.	179.241																							179.241				
#2 CAPITAL	0 ¹																0.35	2.88	22.68	90.77	146.9	132.86	104.95	94.81		596.		
OPS. & MAINT.																												
DECOMMISSIONING																												
POST OPS.																												
AFR STORAGE																												
#1 CAPITAL																												
LAND																												
WORKING CAPITAL																												
OPS. & MAINT.																												
DECOMMISSIONING																												
#2 CAPITAL																												
LAND																												
WORKING CAPITAL																												
OPS. & MAINT.																												
DECOMMISSIONING																												

¹ Undiscounted Net – Still Contributes to Discounted Value

TABLE A-6. UNDISCOUNTED COST MATRIX - CASE 1
HIGH FLOW, VENTURE METHODOLOGY
1978 \$ M

Category Cost Center	Capital	O&M	Trust Funds	Other	Total
Geo. Rep.	596	1199	514		2309
Encap.	290	201	20		511
AFR	2094	160	44		2298
Trans				417	417
R&D				560	560
Gov. Overhead				195	195
Total	2980	1560	578	1172	6290

TABLE A-7. UNDISCOUNTED COST MATRIX - CASE 2
HIGH FLOW, CAMPAIGN METHODOLOGY
1978 \$ M

Category Cost Center	Capital	O&M	Trust Funds	Other	Total
Geo. Rep.	1013	1882	580		3475
Encap.	492	309	23		824
AFR	1849	136	44		2029
Trans.				417	417
R&D				560	560
Gov. Overhead				234	234
Total	3354	2327	647	1211	7539

TABLE A-8. UNDISCOUNTED COST MATRIX - CASE 3
 LOW FLOW, VENTURE METHODOLOGY
 1978 \$ M

Category Cost Center	Capital	O&M	Trust Funcs	Other	Total
Geo. Rep.	595	1645	514		275
Encap.	290	234	20		544
AFR					0
Trans.					0
R&D				560	560
Gov. Overhead				234	234
TOTAL	886	1879	534	794	4093

TABLE A-9. UNDISCOUNTED COST MATRIX - CASE 4
 LOW FLOW, CAMPAIGN METHODOLOGY
 1978 \$ M

Category Cost Center	Capital	O&M	Trust Funds	Other	Total
Geo. Rep.	596	1313	258		2167
Encap.	290	172	10		472
AFR					0
Trans.					0
R&D				560	560
Gov. Overhead				195	195
TOTAL	886	1485	268	755	3394

TABLE A-10. CONTINGENCY COSTS
1978 \$ M

	Case 1 High Venture	Case 2 High Campaigr	Case 3 Low Venture	Case 4 Low Campaign
Capital (nominal value) Geo. Rep.(22%) ¹	92	120	92	92
Encap.(22%) ²	56	73	56	56
AFR (25%) ³	100	100		
Post Operations	357	404	357	179
TOTAL ⁴	605	697	505	327
Percent of Life Cycle	10	9	12	10

¹Reference III-4, Base excludes owner's cost

²Assumed 22 percent of Capital excluding Owner's Cost

³Reference V-1, Base excludes Owner's Cost

⁴Excludes unspecified Geologic Repository C&M Contingency Costs

TABLE A-11. PRIVATE AFR CAPITALIZATION COSTS TO THE GOVERNMENT
 12% DISCOUNTED RETURN AFTER TAXES

CASE NO.	AFR NO.	AFR LIFE	ANNUAL CHARGE
1	1	15	73.9
1	2	13	75.7
2	1	13	75.7
2	2	11	78.6

APPENDIX B. DETAILED PRICE RESULTS

This Appendix presents the breakdown of price results by cost center for dollars per kilogram (Table B-1) and mills per kilowatt hour (Table B-2). Both breakdowns were derived by dividing the final price in proportion to the present value of the expenditure data of the respective cost center. Therefore, there is no relationship between use of a particular facility by a particular shipment of spent fuel and its price. The data shown in Table B-1 is presented graphically in Figure 12-1.

TABLE B-1. PRICE RESULTS IN \$/KGU BY COST CENTER

	Case 1 High Venture	Case 2 High Campaign	Case 3 Low Venture	Case 4 Low Campaign
Geologic Repository	52	54	65	74
Encapsulation	14	15	17	20
AFR	51	38	0	0
Transportation	7	6	0	0
R&D	23	18	29	35
Government Overhead	5	3	5	6
TOTAL	152	134	116	134

TABLE B-2. PRICE RESULTS IN MILLS/KILOWATT-HOUR
BY COST CENTER

	Case 1 High Venture	Case 2 High Campaign	Case 3 Low Venture	Case 4 Low Campaign
Geologic Repository	.245	.259	.307	.344
Encapsulation	.066	.073	.079	.094
AFR	.238	.168	0	0
Transportation	.034	.027	0	0
R&D	.109	.083	.133	.163
Government Overhead	.021	.018	.024	.026
TOTAL	.713	.628	.543	.627

Appendix C. Formulas for Computation of Spent Fuel Management Price

This appendix contains the formulas, variables, and parameters used in this study to calculate the price of spent fuel management.

General Formulas

$$P_b = PV(TC)/PV(Q) \quad (1) \text{ where}$$

$$P_b = \text{Price per unit of spent fuel computed as of the initial base year, } b$$

$$P_{ib} = [PV(C_i)/PV(TC)]P_b \quad (2) \text{ where}$$

$$P_{ib} = \text{Component of price attributed to the } i\text{-th cost center}$$

$$PV(TC) = \sum_{i=1}^m \sum_{j=1}^{n_i} PV(C_{ij}) \quad (3) \text{ where}$$

$$PV(C_{ij}) = \text{Present value of } j\text{-th facility in } i\text{-th cost center}$$

$$PV(TC) = \text{PV of total costs}$$

$$PV(Q) = \sum_{t=y-b}^{S_z-b} \frac{Q_t}{(1+r)^t} \quad t=0,1,2,\dots \quad (4) \text{ where}$$

$$Q_t = \text{Units of spent fuel delivered to the government in year } y=b, b+1, \dots, S_z$$

$$S_z = \text{End year of scenario } z.$$

$$b = \text{Base year for calculation. Initial base year} = 1973.$$

$$r = \text{Discount rate for government revenues.}$$

$$n_i = \text{Number of facilities in } i\text{-th cost center.}$$

$$m = \text{Number of cost centers.}$$

Formulas for the PV costs associated with the cost centers follow.

1. Formulas for AFR Costs (C_{1j})

$$PV(C_{1j}) = \sum_{t=y-b}^{S_z-b} \frac{C_{1jt}}{(1+d)^t} + \frac{TR_1}{(1+d)^{S_z-b}} \quad (1-1) \quad \text{where}$$

$$TR_1 = \text{Trust fund for decommissioning} = \sum_{t=0}^2 \frac{DC_{1t}}{(1+d)^t} \quad \text{where}$$

DC_{1t} = Annual decommissioning costs for an AFR

d = Discount rate for government costs

C_{1jt} = Cost of j-th AFR in t-th year with

$$C_{1jt} = OM_{1jt} + FCR(k, N_{1j}, M)PV(K_{1j}) + CRF(k, N_{1j}) \left[\frac{PV(L_{1j}) + WC_{1j}}{(1+r)} \right] \left[1 - \frac{1}{(1+k)^{N_{1j}}} \right] \quad (1-2) \quad \text{where}$$

OM_{1jt} = O&M costs for j-th AFR in t-th year. Note O&M is not defined to include property taxes and insurance, but it may be redefined to include these ad valorem charges if the FCR is defined to exclude them.

FCR(k, N_{1j}, M) = Fixed Capital Recovery Factor (formulated below).

K_{1jt} = Plant and capital equipment costs expended in year t for the j-th AFR excluding land and land rights.

$$PV(K_{1j}) = \sum_{t=y-b}^{B_{2j}-b} \frac{K_{1jt}}{(1+k)^{t-B_{2j}+b}} \quad \text{for } y=b, b+1, \dots, B_{1j}, \quad (1-3)$$

k = After tax discounted return expected by private owner(s) of the AFRs.

N_{1j} = Operating life of j-th AFR equal to E_{1j} - B_{1j} + 1, where

E_{1j} = Last year in which fuel elements are ever stored in j-th AFR or in which OM_{1j} > 0, whichever comes last. Note, E_{1j} assumed ≤ S_z.

B_{1j} = First year of beneficial use of j-th AFR.

M = Mode of depreciation = 1, 2, or 3 corresponding to straight-line (SL), sum of years digits (SYD) or double-declining balance (DDB) depreciation.

$$CRF(k, N_{1j}) = \frac{k(1+k)^{N_{1j}}}{(1+k)^{N_{1j}-1}} \quad (1-4)$$

$$PV(L_{1j}) = \sum_{t=y-b}^{B_{1j}-b} \frac{L_{1jt}}{(1+k)^{t-B_{1j}+b}} \quad \text{for } y-b, b+1, \dots, B_{1j} \quad (1-5).$$

Note, include annual land taxes in O&M.

WC_{1j} = Working capital for j-th AFR (assumed to be recognized in year B_{1j}).

L_{1jt} = Cost of land and land rights incurred in t-th year for j-th AFR.

τ = Effective federal and local income tax rate borne by private AFR.

$$FCR(k, N_{1j}, M) = \frac{CRF(k, N_{1j})}{(1-\tau)} \left[1 - \alpha - \tau D(M) + \frac{(1-\tau)(\beta_1 + \beta_2)}{CRF(k, N_{1j})} \right] \quad (1-6) \quad \text{where}$$

α = Effective income tax credit (ITC) adjusted for equipment content of AFR.

$D(M)$ = Depreciation factor for M-th mode of depreciation.

$$D(1) = [N_{1j} CRF(k, N_{1j})]^{-1} \quad (1-7)$$

$$D(2) = 2[N_{1j}(N_{1j}+1)k]^{-1} \cdot [N_{2j} - \frac{1}{CRF(k, N_{1j})}] \quad (1-8)$$

$$D(3) = (2/N_{1j})(1+k)[k + 2/N_{1j}]^{-1} \quad (1-9)$$

β_1 = Property tax rate (Decimal Fraction of value of plant and equipment).

β_2 = Insurance rate (Decimal Fraction of value of plant and equipment).

3. Formulas for Encapsulation Facility Costs (C_3)

$$PV(C_{3j}) = \sum_{t=y-b}^{S_z-b} \frac{C_{3jt}}{(1+d)^t} - \sum_{t=y-b}^{B_{3j}-b} K_{3jt} \left[1 - \frac{(S_z-B_{3j}+1)}{DL_3} \right] + \frac{CQ_{3j} TR_3}{UQ_{3j}(1+d)^{S_z-b}} \quad \begin{matrix} \text{if } S_z-B_{3j}+1 \geq DL_3 \\ \text{if not, } S_z-B_{3j}+1 = DL_3 \end{matrix} \quad (-)$$

$$C_{3jt} = OM_{3jt} + K_{3jt}, \text{ where}$$

$$OM_{3jt} = \text{O\&M costs for } j\text{-th encapsulation site in } t\text{-th year.}$$

$$K_{3jt} = \text{Plant and Capital equipment costs expended in the } t\text{-th year for the } j\text{-th encapsulation facility.}$$

$$CQ_{3j} = \text{Cumulative spent-fuel stored in } j\text{-th site at end of scenario life.}$$

$$UQ_{3j} = \text{Ultimate capacity for spent fuel in the } j\text{-th site if fully utilized under scenario rules.}$$

$$TR_3 = \text{Trust Fund for decommissioning} = \sum_{t=0}^6 \frac{DC_{3t}}{(1+d)^t}, \text{ where}$$

$$DC_3 = \text{Annual decommissioning costs for encapsulation sites.}$$

$$B_{3j} = \text{First year of beneficial use of } j\text{-th encapsulation site.}$$

$$DL_3 = \text{Designated depreciation life of encapsulation site.}$$

5. Formulas for Geological Site Costs (C_5)

$$PV(C_{5j}) = \sum_{t=y-b}^{S_z-b} \frac{C_{5jt}}{(1+d)^t} - \frac{\sum_{t=y-b}^{B_{5j}-b} K_{5jt} \left[1 - \frac{(S_z - B_{5j} + 1)}{DL_5} \right]}{(1+d)^{S_z-b}} + \frac{CQ_{5j}}{UQ_{5j}} \left[\frac{TR_5 + A}{(1+d)^{S_z-b}} \right] \quad (5-1)$$

if $S_z - B_{5j} + 1 \geq DL_5$

if not, $S_z - B_{5j} + 1 = DL_5$

$$C_{5jt} = OM_{5jt} + K_{5jt} \quad \text{where}$$

OM_{5jt} = O&M costs for j-th geologic site (excluding encapsulation) in t-th year.

K_{5jt} = Plant and capital equipment costs (ex., encapsulation) expended in t-th year for the j-th geologic site including land and land rights.

CQ_{5j} = Cumulative spent-fuel stored in j-th site at end of scenario life.

UQ_{5j} = Ultimate capacity for spent fuel in the j-th site if fully utilized under scenario rules.

TR_5 = Trust Fund for decommissioning = $\sum_{t=0}^6 \frac{DC_{5t}}{(1+d)^t}$ where

DC_{5t} = Annual decommissioning costs for geological site.

B_{5j} = First year of beneficial use (ex., encapsulation) of j-th geologic site.

DL_5 = Designated depreciation life for geologic site.

A = Value of annuity purchased in last year of Scenario which will provide required annual funding for post operational activities from year $S_z + 1$ onward.

A = a/i where

a = Annual cost of post operational activities.

i = Rate of annuity interest.

6. Formulas for Government Transportation Costs (C_6)

$$PV(C_6) = \sum_{t=y-b}^{S_z-b} \frac{C_{6t}}{(1+d)^t} \quad (6-1) \quad \text{where}$$

C_{6t} = Cost to government for transportation in the t-th year. Other notation as before.

Note the above formula would also apply to government overhead costs (C_8).

7. Formulas for R&D Costs (C_7)

$$PV(C_7) = \sum_{t=y-b}^{S_z-b} \frac{C_{7t}}{(1+d)^t} + C_{7b} \quad (7-1) \text{ for } y=b, b+1, \dots, S_z, \text{ where}$$

C_{7b} = R&D costs chargeable to the program incurred prior to the initial base year of 1978.

All other notation as above.

Table C-1. Variables

Variable	Symbol	I/O	Units
System price (baseyear b)	P_b	0	\$Million (1978)/tonne
Price components	P_{ib}	0	\$Million (1978)/tonne
PV total costs	$PV(TC)$	0	1978\$, Millions
PV cost of j-th facility in i-th cost center	$PC(C_j)$	0	1978\$, Millions
PV cost of i-th cost center	$PV(C_i)$	0	1978\$, Millions
Number of facilities in n_i j-th cost center	n_i	I	1 or 2 digits
Number of cost centers	m	I	1 or 2 digits
Quantity shipped in t-th year	Q_t	I	Tonnes per year
End year of scenario z	S_z	I	4 digits
Base year	b	I	4 digits
AFR annual O&M costs*	OM_{1jt}	I	1978\$, Millions
AFR annual capital costs (ex., land)	K_{1jt}	I	1978\$, Millions
AFR annual land costs	L_{1jt}	I	1978\$, Millions
AFR working capital	WC_{1j}	I	1978\$, Millions
AFR operating life	N_{1j}	I	Years
AFR end year	E_{1j}	I	4 digits
AFR beneficial year	B_{1j}	I	4 digits
Annual decommissioning costs	DC_{1t}	I	1978\$, Millions
Encapsulation annual O&M costs	OM_{3jt}	I	1978\$, Millions
Encapsulation annual capital costs	K_{3jt}	I	1978\$, Millions
Encapsulation beneficial year	B_{3j}	I	4 digits

*Include land property tax in variable.

Table C-1. Variables (Continued)

Variable	Symbol	I/O	Units
Geologic annual O&M costs	OM _{5jt}	I	1978\$, Millions
Geologic annual decommissioning costs	DC _{5jt}	I	1978\$, Millions
Geologic annual capital costs	K _{5jt}	I	1978\$, Millions
Annual surveillance costs	a	I	1978\$, Millions
Geologic beneficial year	B _{5j}	I	4 digits
Annual transportation costs	C _{6t}	I	1978\$, Millions
Annual R&D charges	C _{7t}	I	1978\$, Millions
R&D charges before 1978	C _{7b}	I	1978\$, Millions
Government overhead costs	C _{8t}	I	1978\$, Millions

Table C-2. Parameters

Parameter	Symbol	Default Value
Revenue discount rate	r	0.065
Cost discount rate	d	0.065
Private return rate	k	0.12
Effective income tax rate	τ	0.50
Effective income tax credit	α	0.06
Property tax rate (AFR)	β_1	.015
Insurance rate (AFR)	β_2	.005
Depreciation mode	M	3
Depreciation life of encapsulation	DL_3	10
Depreciation life of geologic site	DL_5	10
Annuity interest	i	0.065

Appendix D. Proof of Equivalence of Capital Recognition Procedure to Interest/Depreciation Procedure for Government Capital Costs

The notation used is as follows:

C = Government capital charge in a particular year.

i = Government cost discount and imputed interest rate.

w = Number of years (or other unit) between time capital charge incurred and first beneficial use of capital.

n = Number of years of beneficial use of capital.

t = Time index.

If the simple procedure is used, C will be recognized in the year incurred. Without loss of generality, recognition can be assumed to occur in the base year, so the cost to the government would simply be C.

On the other hand, the recognition procedure might be:

- Recognize only interest charges on capital (C) until the first year of beneficial use.
- When beneficial use starts, recognize:
  - Annual depreciation charges (assumed to be based on the straight line mode), and
  - Interest charges on undepreciated capital.

The PV of the above charges relative to the year of the investment (i.e., the base year) is:

$$iC \sum_{t=0}^{w-1} \frac{1}{(1+i)^{t+1}} + \frac{1}{(1+i)^w} \left[C/n \sum_{t=1}^n \frac{1}{(1+i)^t} + iC \sum_{t=1}^{n-1} \frac{(1-t/n)}{(1+i)^{t+1}} \right]$$

Note that costs are assumed to occur at the beginning of a year while interest is not due until the end of the year.

The first term of the above expression represents the PV of interest during construction, while the second term is the PV of depreciation charges and interest on undepreciated capital.

To evaluate the first term, substitute:

$$x = \frac{1}{1+i} \quad \text{and} \quad 1-x = \frac{i}{1+i}, \quad \text{or}$$

$$\text{PV(Interest during construction)} = C \left[(1-x) \sum_{t=0}^{w-1} x^t \right] = C \left[\frac{(1-x)(1-x^w)}{(1-x)} \right] = C - Cx^w.$$

After the x -substitution, the discount factor which multiplies the bracketed variables is simply x^w . Therefore, the PV on depreciation charges and interest on undepreciated capital is x^w times the variables in the bracket.

Using the notation from the previous page, the PV of depreciation and interest charges during beneficial use can be expressed as x^w times the following:

$$C/n \sum_{t=1}^n \frac{1}{(1+i)^t} + iC \sum_{t=0}^{n-1} \frac{(1-t/n)}{(1+i)^{t+1}} = C \left[1/n \sum_{t=1}^n \frac{1}{(1+i)^t} + \frac{i}{1+i} \sum_{t=0}^{n-1} \frac{1}{(1+i)^t} - \frac{i}{n(1+i)} \sum_{t=0}^{n-1} \frac{t}{(1+i)^t} \right]$$

Substituting $x = \frac{1}{1+i}$, we have:

$$\begin{aligned} C \left[1/n \sum_{t=1}^n x^t + (1-x) \sum_{t=0}^{n-1} x^t - \frac{(1-x)}{n} \sum_{t=0}^{n-1} tx^t \right] &= C \left[1/n \sum_{t=1}^n x^t + (1-x) \sum_{t=0}^{n-1} x^t - \frac{x(1-x)}{n} \sum_{t=0}^{n-1} tx^{t-1} \right] \\ &= C \left[1/n \sum_{t=1}^n x^t + (1-x) \sum_{t=0}^{n-1} x^t - \frac{x(1-x)}{n} \frac{d}{dx} \sum_{t=0}^{n-1} x^t \right] \end{aligned}$$

Using the geometric sum formula, the PV of depreciation and interest charges are:

$$C \left[\frac{x}{n} \left(\frac{1-x^n}{1-x} \right) + \frac{1-x}{1} \left(\frac{1-x^n}{1-x} \right) - \frac{x(1-x)}{n} \frac{d}{dx} \left(\frac{1-x^n}{1-x} \right) \right] \text{ or}$$

$$C \left\{ \frac{x}{n} \left(\frac{1-x^n}{1-x} \right) + \frac{1-x^n}{1} - \frac{x}{n} \left[\frac{(1-x)(-nx^{n-1}) - (1-x^n)(-1)}{(1-x)^2} \right] \right\} \text{ or}$$

$$C \left\{ \frac{x}{n(1-x)} \left[(1-x^n) + (1-x)nx^{n-1} - (1-x^n) \right] + 1-x^n \right\} \text{ or}$$

$$C \left\{ \frac{x}{n(1-x)} \left[(1-x)nx^{n-1} \right] + 1-x^n \right\} = C \left[\frac{nx^{n-1}}{n} + 1-x^n \right] = C$$

Accordingly, when C is discounted to the base year by the factor x^W , we have $C = Cx^W$ (PV of interest during construction) + x^WC (PV of depreciation and interest on undepreciated capital) which equals C.

Note that the above proof depends on:

- Absence of income taxes.
- Use of same value for the discount and interest rate.