An Order of Magnitude Cost Appraisal for Selected Aspects of Clad Waste Management

by
G. E. Zima

February 1977

**Prepared for the Energy Research
and Development Administration
under Contract EY-76-C-06-1830**

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5295 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.50
026-050	\$5.00
051-075	\$5.50
076-100	\$6.00
101-125	\$6.50
126-150	\$7.00
151-175	\$7.75
176-200	\$8.50
201-225	\$8.75
226-250	\$9.00
251-275	\$10.00
276-300	\$10.25

3 3679 00062 5964

BNWL-2185
UC-70

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SUMMARY

A simple formula, incorporating the fixed charge rate principle, is applied to a clad waste management exercise involving densification, canning, transportation and salt disposal. For the purpose of comparison with the bulk of published nuclear waste management costs, cost and fixed charge rate data appropriate to roughly the period 1970-1973 are used.

Within the context of this order of magnitude appraisal, densification displays some cost advantage, reflected principally in the transportation cost. Dependent on the degree of densification, above a certain clad waste generation rate the transportation savings may be expected to exceed reasonable densification costs. There is no explicit consideration of the decontamination step in this appraisal. The limited accessibility of surface effect decontamination to internal transuranic and activation product contamination suggests a quite small influence of decontamination on the transportation and disposal costs. Decontamination may, however, have a significant effect on the ease of establishing a practicable containment envelope of high reliability throughout the clad waste history.

A brief comparison is made of clad waste management costs with the major costs of the nuclear power economy. This comparison implies a virtually unlimited technical latitude for clad waste treatment in accommodating the public safety without significant perturbation of nuclear power costs. It is submitted that clad waste management optimization will be under the primal constraint of maximizing the long term public safety, with economic analysis useful only as a discriminator between waste handling alternatives of sensibly equivalent containment qualities.

Some areas of clad waste treatment meriting increased attention are noted.

CONTENTS

SUMMARY	ii
INTRODUCTION	1
CONCLUSIONS AND RECOMMENDATIONS	1
A RELATION OF PROCESS DIRECT CAPITAL COSTS TO POWER COST EFFECT.	5
APPLICATION OF THE FCR FORMULA TO A CLAD WASTE MANAGEMENT EXERCISE INVOLVING DENSIFICATION, CANNING, TRANSPORTATION, AND DISPOSAL.	9
AN ORDER OF MAGNITUDE RELATION OF VARIOUS CLAD WASTE MANAGEMENT STEPS TO OTHER COSTS OF NUCLEAR POWER ECONOMY	22
CONSIDERATIONS IN OPTIMIZATION OF CLAD WASTE MANAGEMENT	26
REFERENCES.	28
APPENDIX A	
COMPOSITION AND CALCULATION OF FIXED CHARGE RATE	A-1
APPENDIX B	
OUTLINE OF CALCULATION PROCEDURE FOR VARIOUS CLAD WASTE MANAGEMENT STEPS	B-1
Densification	B-1
Canning	B-5
Transportation	B-6
Disposal.	B-9
Summary	B-10

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INTRODUCTION

It may be expected that economic constraints will be secondary to public safety constraints in the evolution of nuclear waste management strategy. Simple, reasonably comprehensive, procedures for estimating the nuclear power cost effect of various conceivable steps in waste control will, however, be useful in preliminary analysis. This report discusses the application of a simple formula, incorporating the fixed charge rate principle, to a clad waste management exercise involving densification, canning, transportation and salt disposal.

The formula is applied to clad waste generated by a LWR(U) nuclear economy, using: 33 GWd/MT burnup; Diablo Canyon waste model; reprocessing and transport/disposal at 0.4 and 1 year age, respectively. The formula is also used to suggest an order of magnitude cost relation of the clad waste management steps to the major components of nuclear power cost, namely; exploration/mining/milling of uranium, refining/conversion, enrichment, fuel fabrication, and reprocessing/waste management. Cost data are taken largely from ORNL and PNL sources. The formula itself derives from information from several ERDA contractors, principally ORNL and the NUS Corporation.

CONCLUSIONS AND RECOMMENDATIONS

This report discusses a simple procedure for giving order of magnitude power cost effect data (mills/kWh) for various clad waste management steps. The input data are direct capital cost and the associated nuclear power generation served by the waste management step, usually the least ambiguous and most easily obtained information in such cost analysis.

Within the limits of this study, transportation and densification costs dominate the clad waste costs. For a reprocessing-disposal site network requiring an average transport distance of 1000 miles, the transport-savings resulting from densification becomes equal to the densification cost at roughly the following installed rated power levels (80% load factor), for the various densities considered in this report:

<u>Bulk Density (g/cm³)</u>	<u>Installed Rated Power (GWe)</u>	<u>Clad Waste Output (MT/yr)</u>
3.3 (rolled)	125	920
4.5 (die-compacted)	90	662
6.5 (ingot)	55	405

An examination of the cost structure for the various clad waste steps considered here indicates the following qualitative dependence of the power cost effect (mills/kWh) on the installed net power level (GWe x load factor) and clad waste bulk density.

- Densification: The power cost effect decreases with increasing installed net power level. The equipment, related maintenance and building cost components decrease with net power level in accordance with the scaling laws appropriate to these components. Building costs tend to dominate densification (and other clad waste steps requiring special building accommodation). Once the decision to densify is made, the total power cost effect for densification is expected to be a weak function of the density target (i.e., the dominant building costs for rolling are not expected to be much less than those for full densification [melting]).
- Canning: In this appraisal, a constant unit cost is assigned to a given can size, without regard for the cost of the building and equipment requirements pertinent to the canning step. Under this assumption, the power cost effect for the canning step is, for a given can size, inversely proportional to the clad waste bulk density and independent of the installed power level. Where there is no densification, the capital costs of the canning step are relatively prominent and would

require consideration in a more detailed appraisal. With various degrees of densification, the canning step would probably be close coupled in time and facilities to the densification step. The capital cost estimates made in this appraisal for the densification step, particularly for the building requirement, are probably sufficient to include the canning step as well.

- Transportation: The transportation component of cost is a complex of many factors specific to the waste being handled (exposure, composition, age, etc.) and to the transportation network (distance; local, state, and Federal laws pertaining to the transport; public hazard specifics of the route, etc.). Under the assumptions for the transport cost used in this order of magnitude analysis, the total transport power cost effect is composed of terms containing both density and net power level, as well as terms containing some function of density only. For a given installed net power level, the transportation cost effect decreases with density increase; for a given density, the cost effect may vary in a complex manner with power level, depending on the density and the transport specifics. Both the thermal power dissipation and radiological shielding requirements of the clad waste affect the technology and costs of the transportation step through their limitations on shipping cask design and the various safety-related limitations on transport schedules, routes, etc. Out to a few decades beyond reactor discharge, these characteristics of clad waste are largely controlled by the neutron activation products of the waste (a function of the pre-exposure composition of the various metals comprising the clad waste, reactor burnup, age). Essentially surface-limited decontamination procedures would have little effect on the bulk content of these activation products. The contamination of clad waste by spent fuel TRUs and fission products may, however, be substantially reduced by surface-type decontamination. These latter products could be highly significant to breach-of-containment scenarios involving clad waste. In this respect, decontamination may be effective in reducing containment redundancy and expanding the route options for the transportation step.

- Disposal: With a given disposal facility, the unit cost of disposal (cost/can of waste) has been found (ORNL analysis) to be proportional to a term representing the sum of the products of the intensity (time-of-disposal thermal power per some parameter of the waste, e.g., W/kg, W/ft of can length, etc.) and the persistence (half-life) for the isotope array accounting for the thermal power of the waste. The economics of the disposal facility dictate some minimum unit disposal cost. The technology and safety considerations impose some maximum limit on the unit disposal cost. For cases exceeding the maximum, additional aging of the waste is one recourse. Where the minimum limit applies (as in this appraisal for all cases except the rolled waste in 24-in. cans), the disposal cost effect is:
 - directly proportional to the number of cans of waste/GWe of installed net power, which is:
 - directly proportional to the clad waste output/GWe
 - inversely proportional to the weight/can; for a given can, inversely proportional to the bulk density of the waste
 - independent of the installed net power level, assuming that the aggregate capacity of the disposal facilities is held in roughly a constant relationship to the installed net power level.

Where the "true" unit cost applies, the disposal cost effect is:

- directly proportional to the time-of-disposal thermal power of the clad waste/unit of net power (W/GWe)
- directly proportional to the $\$/\text{ft}^2$ of net disposal site area
- inversely proportional to the areal (W/ft^2) power density assigned the waste for a given disposal facility
- independent of the installed net power level (see above).

The crucial objective of clad waste management is maximizing the containment quality of the clad waste and its ancillaries. Densification appears to be one obvious recourse toward this objective. The role of

decontamination is less clear. Some aspects of clad waste management related to these problems, and meriting more attention, are as follows:

- practicability of available techniques for densification, and corresponding density targets, for clad waste of various compositions (metal mix) and reactor exposure,
- rate of generation, safety implications, and practical control techniques for metal fines produced during the various operations of the fuel assemblies and clad waste,
- quantitative measures for the effect of densification on the containment qualities of unclad waste, and waste with cladding/containment systems representing progressively more redundant containment concepts,
- more extensive data on the short- and long-range safety implications of clad waste as a function of: reactor type, fuel type, exposure history, fuel assembly materials (cladding and cladding contiguous materials are of principal interest),
- practicability of various methods and degrees of decontamination for clad waste; better identification of the net impact of clad waste decontamination on the overall nuclear waste management program, and
- technical feasibility and safety implications of various degrees of consolidation of clad waste with densified forms of high-level waste (HLW) into a unit for common disposal.

A RELATION OF PROCESS DIRECT CAPITAL COSTS TO POWER COST EFFECT

An appropriate fixed charge rate (abbreviated FCR hereinafter) can be used to simplify the discounted cash flow analysis generally used for power cost analysis.⁽¹⁾ The specific FCR depends on a number of factors and assumptions regarding the magnitude and phasing of costs and incomes (see Appendix A), the ownership of the facility (public or private, or composite), type of financing. For private ownership, a FCR range of $22.5 \pm 7.5\%$ was noted in WASH-1099 (December 1971). In a comprehensive 1975 analysis of reprocessing costs, Finney et al.⁽²⁾ suggested that a FCR of 26% was appropriate for

private ownership of non-power-plant facilities associated with the nuclear power economy. For the nuclear power plant, a FCR of 13.5% was recommended by the AEC System Analysis Task Force as appropriate for cost analysis of this component for early 1970's dollars.^(1,3)

Direct capital cost items of present concern are listed in Table 1, together with indirect capital cost items.

TABLE 1. Direct and Indirect Capital Cost Items⁽²⁾
of Fixed Charge Cost

Direct

- Equipment
- Installation (including piping, instrumentation, controls)
- Modification to allow for remote maintenance
- Building (remote and/or contact maintenance cells/rooms)
(i.e., total direct capital cost is for complete
installed equipment cost, including building)

Indirect

% of Direct
Cost

• Engineering and supervision	15
• Construction Expense, Contractor's Fee	20
• Engineering Design	19
• Quality Assurance	6
• Other Owner's Costs	10
• Contingency	40
• Interest During Construction (8%/yr, over 5-year period)	<u>39</u>

Total 149%

Operating/Maintenance Cost assumed to be 40% of total fixed charge cost.

The power cost effect associated with the above capital costs will be expressed as mills/kWh, a cost index that relates directly to economic analysis of power generation.⁽⁴⁾ The formula that expresses power cost effect assignable to a given waste management step without charge-cost displacement, as a function of direct capital costs is, therefore:

$$\Delta \$_i \text{ (mills/kWh)} = \frac{1.142 \times 10^{-4} \times [\text{FCR}_i] \times [\text{CAPD}_i] \times [1 + \emptyset_{\text{ICC}}^i] \times [1 + \emptyset_{\text{OM}}^i]}{P \times L} \quad (1)$$

where

1.142×10^{-4} is a unit conversion factor computed as follows,

$$1.142 \times 10^{-4} = \frac{10^6 \text{ mills}/(10^3 \$)}{(10^6 \text{ kW/GW}) \times (8760 \text{ hr/yr})}$$

FCR_i is the yearly fixed charge rate appropriate to process i
(expressed as fraction)

CAPD_i is the direct capital cost associated with process i (in 10^3 \$'s)

$\emptyset_{\text{ICC}}$ is the multiplier accounting for indirect capital costs (expressed as a fraction)

$\emptyset_{\text{OM}}$ is the multiplier accounting for operating/maintenance expense (expressed as a fraction)

P is the associated installed rated power plant capacity (in GWe)

L is the load factor (fraction of capacity used during year).

Where there is a displacement between the charge for a service and the performance of the service, a discount factor is applied to formula (1), namely,

$$\text{discount factor} = (1 + j_s)^{-n}$$

where j_s is the effective discount rate corresponding to the financing conditions (see Table A-1) and tax rates

n is the discount period (yr).

Incorporating the discount factor into formula (1), the power cost effect summary for a series of clad waste steps can be stated as follows:

$$\Delta \$ \text{ (mills/kWe/hr)} = \frac{1.142 \times 10^{-4}}{P \times L} \sum_i [\text{FCR}_i] \times [\text{CAPD}_i] \times [1 + \emptyset_{\text{ICC}}^i] \times [1 + \emptyset_{\text{OM}}^i] \times (1 + j_s^i)^{-n_i} \quad (1a)$$

where the summation is over the various clad waste management steps corresponding to a given nuclear power economy (PxL), and the i subscripts and superscripts specialize the various factors to the given step if desirable. The FCR appropriate to a given step must be determined in accordance with current economic practice and/or the objectives of the formula use. As noted in Appendix A, different FCRs are used for depreciable and nondepreciable capital costs (e.g., land). The detailing of a given step in the waste management is arbitrary. Those capital cost components of a given step that require a substantially different FCR (and other factors as well) (e.g., land cost as opposed to equipment/building costs, shipping cask costs as opposed to certain freight/handling costs, etc.) should be segregated, although this refinement probably would add very little to the order of magnitude implied in formula (1a).

For the purposes of this report, the recommendations of Finney et al.⁽²⁾ as to the indirect capital cost and operating/maintenance multipliers of direct capital cost ($\emptyset_{ICC}$ and $\emptyset_{OM}$, respectively) will be used, namely (see Table 1),

$$\begin{aligned}\emptyset_{ICC} &= 1.49 \\ \emptyset_{OM} &= 0.40\end{aligned}$$

Substituting these values in formula (1a):

$$\Delta \$_i (\text{mills/kWh}) = \frac{3.981 \times 10^{-4} \times [FCR_i] \times [CAPD_i] \times [1 + \frac{i}{v_s}]^{-n_i}}{PxL} \quad (1b)$$

For example, a reprocessing plant capacity of 1500 MT/yr (spent fuel) would serve a 55 GWe LWR(U) reactor economy at about 80% load factor.^(2,3) The power cost effect for a given waste management step serving this capacity would be:

$$\Delta \$_i (\text{mills/kWh}) = 9.048 \times 10^{-6} \times [FCR_i] \times [CAPD_i] \times [1 + \frac{i}{v_s}]^{-n_i}$$

For power cost effect estimates where the discounted cash flow procedure is inappropriate, or the available cost data already reflect certain elements of the discounted cash flow procedure, the power cost effect is estimated from the following expression, obtained by eliminating the FRC and capital multiplier factors from relation (1a), namely:

$$\Delta \$_i (\text{mills/kWh}) = \frac{1.142 \times 10^{-4} \times [\text{CAPD}_i] \times [1 + \frac{i}{v_s}]^{-n_i}}{P \times L} \quad (1c)$$

The canning and disposal power cost effects of this appraisal are estimated using the above relation.

APPLICATION OF THE FCR FORMULA TO A CLAD WASTE MANAGEMENT EXERCISE INVOLVING DENSIFICATION, CANNING, TRANSPORTATION, AND DISPOSAL

Considering the current volume of waste management literature, there has been very little analysis of the problems specific to clad waste. Depending on the extent of contamination by spent fuel fission products and transuranics, clad waste could present a significant radiological hazard at various stages of the generation to disposal history.⁽⁵⁾ Furthermore, the volume of clad waste generated by the chop-leach process, in die-compacted form, is virtually equal to that of the associated high level waste in calcined form.⁽⁵⁾ From volume and potential radiological hazard standpoints, therefore, clad waste cannot be accorded a trivial status in the overall nuclear waste management considerations.

Blomeke and Perona⁽⁶⁾ have considered some of the technical and economic factors associated with the storage, shipment and disposal of clad waste from LWR and LMFBR reactors, using a number of ORNL studies relevant to these aspects of clad waste handling. For the LWR case, their cost summary is given in Table 2. The principal assumptions for this analysis are given in the table. This study indicates that interim storage (0, 2, 9 years were considered) is not economically feasible; that densification (uncompacted, rolled, die-compacted forms were considered) is advantageous, specifically with respect to the transportation cost, which included shipping cask cost. Densification cost was not considered in this study.

As an exercise in applying formula (1) to clad waste cost analysis, the 0 year interim storage case of the Blomeke and Perona model is assumed, with the addition of the ingot form of clad waste. In addition to the costs considered by these authors, namely, canning, shipment, and disposal, an attempt is made to estimate the densification cost.

TABLE 2. Cost Summary from Reference 6

[20 GWe LWR(U) Economy, 80% L, 33 GWd/MT
Diablo Canyon Clad Waste Model
23.6% FCR]

Form	Can Diameter (in.)	Burial Age (yr)		
		1 (no int. st.)	3 (2 yr int. st.)	10 (9 yr int. st.)
COST (10^{-3} mills/kWh)				
<u>UNCOMPACTED</u>	24			
Cans		0.6	0.6	0.6
Storage		0	3.5	9.3
Shipment		7.1	5.4	2.2
Disposal		0.4	0.3	0.1
TOTAL		8.1	9.8	12.2
<u>ROLLED</u>	24			
Cans		0.2	0.2	0.2
Storage		0	2.6	5.7
Shipment		3.3	2.5	1.0
Disposal		0.3	0.1	0.1
TOTAL		3.8	5.4	7.0
<u>DIE-COMPACTED</u>	9			
Can		0.4	0.4	0.4
Storage		0	2.5	4.4
Shipment		2.4	1.9	0.7
Disposal		0.7	0.6	0.2
TOTAL		3.5	5.4	5.7

- Contamination by 0.5 w/o of fission products; 0.1 w/o TRUs.
- 2000 mile round trip shipping distance.
- 100 ton (short) shipping cask weight limit.
- Salt mine disposal.
- Reprocessing at 0.4 year age; 0.6 year storage at reprocessing plant.
- Costs for operations conducted at 1 year, 3 years, and 10 years, are present worthed by factors 1.060, 1.339, and 3.036, corresponding to effective interest rate of 12.4% and charge assessment at time of reprocessing.

Using cost data and calculation technique given in Appendix B, the power cost effects for densification, canning, transport and disposal are estimated over the installed rated power range 5 to 1400 GWe, for an 80% load factor. For comparison with the results of Blomeke and Perona⁽⁶⁾ at the 20 GWe installed rated power level, a fixed charge rate of 23.6% is used for the transportation cost component and relation (1c) is used for the canning and disposal cost analysis. In addition to the FCR of 23.6%, their economic assumptions yield a discount interest rate (i_{vs}) of 12.4% (financing is 70% equity, 30% bonds; bond interest is 8%; after tax return on equity is 16%; income tax is 48%; see Table A-1 for calculation of i_{vs}). For this comparison only, the cost of operations conducted about 6 months (0.5 year interest period) after reprocessing, namely, transportation and disposal, include a discount factor of 1.060, based on the 12.4% interest rate.

Table 3 compares power cost effect data obtained with formulas (1b) and (1c) with those of Blomeke and Perona⁽⁶⁾ for the 20 GWe installed rated power level. The agreement between specific cost components and the total cost for a given densification is generally satisfactory for all of the cases considered by these authors. There is no basis for comparison for the fully densified (ingot) case.

The general appraisal over the 5 to 1400 GWe range uses an FCR of 26%. For the zero interim storage case considered here, the discount factor is negligible considering the other cost assumptions and it is not used in this order of magnitude analysis, i.e., formulas (1b) and (1c) are used without the discount factor. Cost data generally pertain to the period 1970-1973. The principal justification for this anachronism is that the bulk of the published cost data on nuclear waste management applies to roughly this period.

Under present cost assumptions, the canning and disposal components of the power cost effect are constant (independent of power level) for a given clad waste bulk density. These components are given in the data summary in Table 4 for the 20 GWe installed rated power level, together with the densification and transportation power cost effects appropriate to this power level.

TABLE 3. Comparison of Cost Data Derived from Formulas (1b) and (1c) with Cost Data from Blomeke and Perona⁽⁶⁾

[LWR(U) case, 20 GWe, Diablo Canyon Model,
one-year age, no interim storage, 23.6% FCR]

Clad Waste Form	<u>Δ\$(mills/kWh)</u>	
	<u>Formulas (1b,c)</u>	<u>Reference 6 (Computer Code)</u>
<u>UNCOMPACTED</u>		
Canning	5.28-4 ^(a)	6.0-4
Transport	7.14-3	7.1-3
Disposal	3.22-4	4.0-4
TOTAL	<u>7.99-3</u>	<u>8.1-3</u>
<u>ROLLED</u>		
Canning	2.10-4	2.0-4
Transport	3.20-3	3.3-3
Disposal	2.55-4	3.0-4
TOTAL	<u>3.67-3</u>	<u>3.8-3</u>
<u>DIE-COMPACTED</u>		
Canning	4.23-4	4.0-4
Transport	2.88-3	2.4-3
Disposal	6.55-4	7.0-4
TOTAL	<u>3.96-3</u>	<u>3.5-3</u>

(a) $5.28-4 = 5.28 \times 10^{-4}$, etc.

note: no basis of comparison for the fully densified (ingot) form.

TABLE 4. Power Cost Effect for Densification, Canning, Transport and Disposal of Clad Waste at Various Bulk Densities

[20 GWe, LWR(U) Economy, 80% Load Factor, 33 GWd/MT
Diablo Canyon Clad Model, 1 year age
23.6 and 26% FCR]

COMPONENT	DENSIFICATION		CANNING ^(b)	TRANSPORT		DISPOSAL	TOTAL	
FCR	23.6	26		23.6	26		23.6	26
POWER COST EFFECT (mills/kWh)								
UNCOMPACTED (1.2 g/cm ³)	0	0	5.28-4	7.57-3	8.34-3	3.42-4	8.44-3	9.21-3
ROLLED (3.3)	1.14-2 ^(a)	1.25-2	2.10-4	3.39-3	3.75-3	2.71-4	1.53-2	1.67-2
DIE-COMPACTED (4.5)	1.14-2	1.26-2	4.23-4	3.05-3	3.36-3	6.94-4	1.56-2	1.71-2
INGOT (6.5)	1.14-2	1.26-2	2.97-4	2.12-3	2.33-3	4.86-4	1.43-2	1.57-2

24 IN. CANS

9 IN. CANS

(a) $1.14-2 = 1.14 \times 10^{-2}$, etc.

(b) 24 in. OD cans used for uncompacted and rolled forms
9 in. OD cans used for die-compacted and ingot forms

The two different can sizes chosen by Blomeke and Perona⁽⁶⁾ (24 and 9 in. OD) represent a compromise among management of the thermal power of the clad waste and canning/transport/disposal efficiency.

The densification and transportation power cost effects are both affected by the scale of operation. It is primarily the relative change in these components that determines the course of the total power cost effect with the installed rated power level. At the 20 GWe level, the transport savings due to densification are not sufficient to offset the densification cost and the uncompacted waste form exhibits the lowest total power cost effect (see Table 4). Table 5 gives the densification and transport power cost effect data as a function of installed rated power level and bulk density. A typical plot of densification power cost effect versus the transport differential due to densification (see footnote--Table 5) is given in Figure 1 for the ingot form. For this case it is seen that near an installed rated power level of 55 GWe the transport differential is about equal to the densification cost. While the densification power cost effect curves for the other densities are virtually identical to the one shown for the ingot form on this scale, the transport differential curves vary considerably. A summary of the "break-even" installed rated power levels for the various densities is as follows:

<u>Clad Waste Bulk Density (g/cm³)</u>	<u>"Break-Even" (GWe)</u>	<u>Clad Waste Output (MT/yr)</u>
3.3	~125	920
4.5	~90	662
6.5	~55	405

Table 6 indicates the relative cost importance of the various clad waste steps for the extreme cases, namely, uncompacted and ingot forms, over a wide range of installed rated power levels. Component and total power cost effect data are also given for the various cases considered in the table. The trend of total power cost effect with rated power level is shown in Figure 2, where characteristics are given for the uncompacted, intermediate and ingot forms. The intermediate forms (rolled, die-compacted) are nearly indistinguishable

TABLE 5. Densification and Transport Power Cost Effects
for Various Densification and Rated Power Levels

[LWR(U) Reactors, 33 Gwd/MT; Diablo Canyon Clad Waste Model,
26% FCR]

		$\Delta \$_{\text{den}}$ (mills/kWh)			$\Delta \$_{\text{tr.}}$ (mills/kWh)			
		Bulk Density (g/cm ³)			Bulk Density (g/cm ³)			
		3.3	4.5	6.5	3.3	4.5	6.5	1.2 (uncompacted)
INSTALLED RATED POWER: (GWe)	5	2.98-2 ^(a)	2.98-2	2.99-2	1.10-2	1.02-2	7.96-3	1.36-2
	10	1.92-2	1.92-2	1.93-2	6.18-3	5.65-3	4.20-3	8.50-3
	20	1.25-2	1.26-2	1.26-2	3.76-3	3.36-3	2.33-3	8.34-3
	30	9.62-3	9.65-3	9.70-3	2.95-3	2.59-3	1.71-3	8.25-3
	40	8.04-3	8.07-3	8.12-3	3.72-3	2.21-3	1.39-3	6.70-3
	50	6.99-3	7.02-3	7.07-3	3.21-3	1.96-3	1.21-3	7.23-3
	55	6.60-3	6.63-3	6.67-3	3.04-3	2.70-3	1.14-3	7.76-3
	60	6.24-3	6.27-3	6.31-3	2.89-3	2.58-3	1.08-3	7.39-3
	70	5.68-3	5.70-3	5.74-3	3.33-3	2.34-3	9.26-4	7.50-3
	80	5.23-3	5.25-3	5.29-3	3.08-3	2.17-3	8.71-4	6.97-3
	90	4.86-3	4.89-3	4.92-3	2.86-3	2.03-3	8.31-4	7.08-3
	100	4.54-3	4.56-3	4.59-3	3.19-3	2.39-3	8.31-4	7.19-3
	250	2.59-3	2.60-3	2.62-3	2.77-3	2.09-3	8.80-4	6.96-3
	500	1.70-3	1.71-3	1.73-3	2.66-3	1.99-3	8.00-4	6.86-3
	1000	1.11-3	1.12-3	1.14-3	2.67-3	1.98-3	7.59-4	6.85-3
	1400	9.05-4	9.13-4	9.24-4	2.65-3	1.98-3	7.42-4	6.86-3

(a) $2.98-2 = 2.98 \times 10^{-2}$, etc.

Note: Transport differential due to densification = $\Delta \$_{\text{tr}} = [\Delta \$_{\text{tr}}]_{\text{UC}} - [\Delta \$_{\text{tr}}]_{\text{DEN}}$

FIGURE 1. Comparison of Power Cost Effect of Densification ($\Delta \$_{den.}$) With Transport Differential Due to Densification As a Function of Rated Power Capacity

TABLE 6. Relative Cost Importance of Clad Waste Steps Over Rated Power
Range of 10 to 1000 GWe

Rated Power (GWe):		10		20		55		250		1000	
Form:		UC ^(a)	INGOT	UC	INGOT	UC	INGOT	UC	INGOT	UC	INGOT
$\Sigma \Delta \$ (\text{mills/kWh}):$		9.37-3 ^(b)	2.42-2	9.21-3	1.56-2	8.63-3	8.59-3	7.83-3	4.28-3	7.72-3	2.68-3
DENSIFICATION	%:	0	79.8	0	80.8	0	77.6	0	61.2	0	42.5
	$\Delta \$_i$:	0	1.93-2	0	1.26-2	0	6.67-3	0	2.62-3	0	1.14-3
CANNING	%:	5.64	1.22	5.73	1.90	6.12	3.46	6.74	6.94	6.84	11.1
	$\Delta \$_i$:	5.28-4	2.97-4	5.28-4	2.97-4	5.28-4	2.97-4	5.28-4	2.97-4	5.28-4	2.97-4
TRANSPORT	%:	90.8	17.4	90.6	14.9	89.9	13.4	88.9	20.6	88.7	28.3
	$\Delta \$_i$:	8.50-3	4.20-3	8.34-3	2.33-3	7.76-3	1.14-3	6.96-3	8.80-4	6.85-3	7.59-4
DISPOSAL	%:	3.65	2.01	3.71	3.12	3.96	5.66	4.37	11.4	4.43	18.1
	$\Delta \$_i$:	3.42-4	4.86-4	3.42-4	4.86-4	3.42-4	4.86-4	3.42-4	4.86-4	3.42-4	4.86-4

(a) Uncompacted (bulk density about 1.2 g/cm³)

Ingot (density about 6.5 g/cm³)

(b) 9.37-3 = 9.37 x 10⁻³, etc.

FIGURE 2. Total Power Cost Effect (Densification + Canning + Transport + Disposal) versus Rated Power for Various Clad Waste Bulk Densities

on this scale and curve "B" is used for both intermediate forms (as noted above, these forms yield slightly different "break-even" values of rated power under present assumptions).

There is obviously much opportunity for refinement of the densification cost data as a function of clad waste throughput and target density. This brief study assumed: a) reasonable contact and remote maintenance building allotments for single and double densification lines; b) the CAPD factor for densification equipment is a weak function of the target density. Under these assumptions, and using cost data of Finney et al.,⁽²⁾ the building costs dominate the densification cost, i.e., substantial changes in densification equipment costs are expected to have relatively little effect on the densification power cost effect. If other possible clad waste steps (e.g. sorting, decontamination) must involve buildings specific to these operations, then it would appear that the true building cost will continue to be the major factor in clad waste steps confined to the reprocessing plant site.

Perona and Blomeke⁽⁷⁾ discuss a computer code for estimation of shipping cask requirements for solidified high-level waste that takes cognizance of the gamma and neutron hazard potential and the thermal power capacity inherent to the waste and that resulting from a "standard fire" involving the cask. Assuming certain technical criteria such as permissible radiation dose rates external to the cask, centerline temperature of the waste, temperature at the base of external cooling fins, the code "designs" a shipping cask for various waste can sizes (6, 9, 12, 24-in. dia) and various cask materials (Fe, Pb, and depleted U) as a function of the age of the waste and the post-reactor discharge nuclide composition of the waste. This, or a similarly oriented code, is needed to help quantify the engineering problems/safety implications associated with the interim storage, shipping, retrievable surface storage if needed, and disposal phases of the clad waste history as a function of: post-chop/leach contamination and composition factors, and clad waste bulk density.

Within the context of this order of magnitude cost appraisal, densification displays some cost advantage. As noted later, the cost variations attributable to densification are, however, trivial within the overall cost perspective of nuclear power. This fact implies a virtually unlimited technical

latitude for accommodating to the fundamental public safety consideration. The containment quality of clad waste and its ancillaries is the crucial criterion. The ability of densification to serve this criterion, over the range of conceivable environmental influences, is not well known. Eventually, the question of densification must also include the practicability of various degrees of consolidation of high-level and clad waste into a unit for common disposal.

Decontamination of nuclear waste is a process that effects some redistribution of various nuclides among an array of waste streams comprised of the original stream(s) plus those generated by the decontamination process. The net effect of this redistribution on nuclear waste management will depend on the resultant change in the flow rate of the various categories of waste which require different containment provisions throughout their history. Decontamination of clad waste might have several objectives, namely: reduction of TRU contamination to expand short- and long-term storage and disposal options under current regulations; general clean-up of particular metals of the waste for reuse in special environments either in their existing condition or as ingredients for remelted stock; general reduction of the nuclide spectrum of the waste to reduce the containment redundancy for the waste throughout its history. The ability of current decontamination procedures to serve some of these objectives is under study.

Depending on the fuel assembly design and the extent of disassembly prior to the chop-leach operation, the clad waste is comprised of various metals in addition to the cladding proper. The Diablo Canyon and Reference Fuel Assembly models represent several appraisals of the possible pre-exposure metal (elemental) mix of the clad waste for LWR reactors with uranium or mixed oxide fuels.⁽⁵⁾ Some degree of classification of clad waste metals according to the type of nuclide contamination is possible through sorting prior to the chop-leach operation; for example, the stainless steel and Inconel components bear the principal burden of activation products, while the fuel cladding bears the principal burden of the TRUs and fission products derived from spent fuel contamination. The extent to which sorting operations of various degrees of selectivity can help serve the above decontamination objectives is a study subject of some practical importance.

Surface effect decontamination has little effect on the bulk content of the neutron activation products that control the thermal power dissipation and radiological shielding requirements important to the transportation, interim storage and disposal steps. Some direct and interpolated data on thermal power that support part of this statement are given in Table 7. Under fairly pessimistic assumptions of contamination of clad waste by spent fuel TRUs and fission products, the activation products (light metal category in table) dominate the thermal power out to about 50 years of age.^(5,6) The radiological shielding requirements depend on the metals comprising the clad waste, the burnup and the age. Activation products from deliberate, or adventitious, constituents of the stainless steels, inconels and zircalloys comprising the clad waste appear to present the greatest problem in this respect. Using the Diablo Canyon clad waste model and a shielding computer code, Blomeke and Perona⁽⁶⁾ state that the shielding requirements are dominated by

TABLE 7. Distribution of Thermal Power Among Nuclide Classes of Clad Waste

Age (yr)	<u>Thermal Power (MW/MTU)^(a)</u>			Percent of Total for Light Metals
	<u>Transuranics</u>	<u>Fission Products</u>	<u>Light Metals</u>	
0.4	4.64-7 ^(b)	9.95-6	6.95-4	98.6
1.4	4.34-7	3.93-6	1.05-4	96.3
10.4	3.95-7	5.10-7	2.71-5	96.8
20	-	interpolated from plot	-	85
40	-	"	-	66
60	-	"	-	43
100	2.11-7	5.25-8	4.26-8	14

- (a) • Data from Reference 5.
 • Diablo Canyon clad waste model.
 • LWR(U) reactor, 33 GWd/MT burnup; 34.03 MTU/GWe/yr.
 • 0.05 w/o spent fuel U and TRUs in clad waste.
 • 0.05 w/o spent fuel fission products in clad waste.
 • 100 w/o light metals in clad waste.

(b) 4.64-7 = 4.64×10^{-7} , etc.

the activation products. The Reference Fuel Assembly model,⁽⁵⁾ containing a higher proportion of stainless steel plus inconel, would be expected to have even greater activation product influence on shielding requirements. Many potential, radiologically important, contaminants of clad waste (e.g., spent fuel TRUs and fission products) are accessible to considerable decontamination by "surface" effect procedures. It is submitted that the real significance of decontamination will be revealed only through technical analysis and optimization of the containment envelop for clad waste, and its subsidiary waste streams, which extends from chop-leach discharge through the disposal phase.

AN ORDER OF MAGNITUDE RELATION OF VARIOUS CLAD WASTE MANAGEMENT STEPS TO OTHER COSTS OF NUCLEAR POWER ECONOMY

Table 8 lists data given by Golan and Salmon⁽⁸⁾ and Timm⁽⁹⁾ for absolute, or relative, costs of various components of the nuclear power economy. Using the 1400 GWe basis, at 80% L, formula (1) was applied to Golan and Salmon's data to obtain power cost effect data for the various components at 26% FCR. The power plant cost effect was obtained using 13.5% FCR and only the operating/maintenance multiplier of formula (1) [this procedure assumes that the quoted capital cost figure includes both direct and indirect costs, an assumption that gives a value for power plant cost effect in reasonable agreement with the 7-10 mills/kWh range cited for the power plant component for near 1972 \$'s.⁽²⁾]

A cost increment for management of HLW and clad waste was obtained using data in Table 9, making no attempt to correct for actual, or implied, FCR values for this order of magnitude comparison. With the addition of the HLW and clad waste cost effects to Golan and Salmon's data, percent of total fuel cycle costs were obtained. These data, together with those of Timm⁽⁹⁾ are given in Table 8. The arbitrary procedure for obtaining the "averaged" power cost effect data (column [G], Table 8) is given at the bottom of Table 8.

Using the "average" cost effect data of Table 8 (totaling 10.4 mills/kWh), the percentage of total nuclear power cost represented by the various

TABLE 8. Total Nuclear Power System Cost Data

[Principally LWR Economy, 80% L
1972 \$'s
26% FCR used for fuel cycle
13.5% FCR used for power plant]

COMPONENT	[A]	[B]	[C]	[D]	[E]	[F]	[G]
Power plant	400 + 6 ^(1,2)	7.7	7.7	-	-	-	7.7
U exploration/mining milling/conversion	7.1 + 6	0.65	0.65	24.3	25	24.8	0.67
U enrichment	16 + 6	1.4	1.4	53.3	34	43.7	1.2
Fuel fabrication	3.5 + 6	0.32	0.32	12.2	13	12.6	0.33
Reprocessing/ waste management	2.0 + 6 ⁽³⁾	0.19	0.28	10.2	28	19.1	0.51
TOTAL	4.29 + 8	10.26	10.35	100	100	100	10.41

[A]: Golan and Salmon ⁽⁸⁾	CAPD(10 ³ \$) data	[F]: Average % of total fuel cycle costs
[B]: Δ \$(mills/kWh) data from [A] using formula (1) of text		from [D] and [E] data
[C]: HLW and clad waste Δ \$(mills/kWh) data (see Table 9) added to [B]		[G]: Averaged Δ \$(mills/kWh) data applying [F]/[D] factor to [C] data
[D]: % of total fuel cycle costs from [C] data		(1): $400 + 6 = 400 \times 10^{+6}$, etc.
[E]: % of total fuel cycle costs from Timm ⁽⁹⁾		(2): Corresponds to 1400 GWe economy (3): Does not include waste management costs beyond local reprocessing plant action

TABLE 9. Power Cost Effect Data for HLW and Clad Waste Management

<u>Disposed Waste/Form</u>	<u>\$(mills/kWh) range</u>	<u>Ref./Assumptions</u>
HLW, liquid or solid	0.024-0.065	Ref. (10) <ul style="list-style-type: none"> • 60.8 GWe LWR(U) economy • borosilicate solid form • 5 yr liquid storage for solid disposal form • 0 yr liquid storage for liquid disposal form • 5 yr interim storage for solid disposal form • 1600 mile roundtrip distance for solid disposal form • 0 distance for liquid disposal form (plant at disposal site) • geologic (rock/salt) disposal • 1973 \$'s
HLW, solid	0.033-0.040	Ref. (11) <ul style="list-style-type: none"> • 20 GWe LWR(U) economy • calcined form • interim liquid storage (0-20 yrs) • interim solid storage (0-5 yrs) • 2000 mile roundtrip distance • geologic (salt) disposal • 1970 \$'s
Clad Waste	0.009-0.02	Present report <ul style="list-style-type: none"> • 20 GWe LWR(U) economy • cost range is for lowest and highest values for densification, canning, transport, disposal total cost • 1972-1973 \$'s

:range for HLW + clad waste: 0.032-0.090 (mills/kWh)
:value for add-on to column [C] (Table 8): 0.090 (mills/kWh)

clad waste steps considered in this report are shown in Table 10 for the 20 and 55 GWe rated power levels. Even with what are regarded as fairly extravagant densification cost assumptions, the densification step is only about 2/10 of 1% of the nuclear power total for the most expensive case considered (20 GWe, double densification line). The total power cost effect for all of the clad waste steps is only about 3/10 of 1% of the total. Correction of the major cost components of Table 8 for rated power level would probably make these relative values even smaller.

TABLE 10. Cost Comparison of Various Clad Waste Management Steps with Total Nuclear Power Cost

Rated Power Level (GWe)	Component Cost ^(a) (mills/kWh)	Percent of Total ^(b)
20	Densification: 1.26-2 ^(c) (no backup)	0.12
	: 2.29-2 (backup)	0.22
	Canning : 2.97-4	0.003
	Transport : 2.33-3	0.021
	Disposal : 4.86-4	0.005
55	Densification: 6.67-3 (no backup)	0.064
	: 1.24-2 (backup)	0.120
	Canning : 2.97-4	0.003
	Transport : 1.14-3	0.011
	Disposal : 4.86-4	0.005

(a) Costs refer to ingot form (see Table 6); 26% FCR where applicable.

(b) Referred to total nuclear power cost of 10.4 mills/kWh (Table 8, column G).

(c) 1.26-2 = 1.26×10^{-2} , etc.

CONSIDERATIONS IN OPTIMIZATION OF CLAD WASTE MANAGEMENT

Although the power cost effect represented by waste management appears to be almost insignificant,^(10,11) the public visibility of nuclear waste handling, and the potential for both reasonable, and unreasonable, debate in connection with nuclear waste, impart a significance to this component that could be a principal determinant of public acceptance of nuclear power. The crucial criterion for a given step within a given waste sector will be: does this step add to, or subtract from, the perpetual protection from harmful nuclear power by-products that is now a well-publicized responsibility of the nuclear power alternative. Waste management strategies developed under this primal guideline of containment reliability may be expected to have very weak constraint from economic factors.

Fleming and Bassioni⁽¹²⁾ give a fairly succinct outline for the optimization of a waste strategy of this nature. The essentials of this "optimization" are as follows:

- The total containment reliability of a waste management system (from generation to ultimate disposal) may be expressed:

$$R_s = \prod_j [1 - (1 - r_j)^{m_j}]$$

where,

r_j is the component reliability of the j 'th step

m_j is the redundancy of the j 'th step.

- The risk of containment breach at the j 'th step is given by:

$$w_j = (1 - r_j)^{m_j} \times Q_j$$

where,

Q_j is the radiological (more generally the biological)

hazard burden associated with the waste at the j 'th step.

- Let w_j be the maximum permissible release risk for the j 'th step, then,

$$w_j \leq W_j$$

- If a cost constraint is to be applied, then,

$$\sum_j a_j m_j \leq C$$

where,

a_j is the cost per "unit" at the j 'th step

C is the "limit" on total cost of the system.

- Total system reliability is the object function, and the optimization consists of finding the set of r_j and m_j values that maximize R_s , subject to a strong constraint from the release risks (w_j) and a weak constraint from the total cost (C).

The "redundancy" referred to by these authors could be generalized to include any factor that affects the containment of the biological hazard burden of the waste. The "unit" could refer to some base, or reference, feature of design. The number of steps in the waste management process will be influenced by the extant Federal, state, and local laws regarding nuclear waste handling.

The problems in quantifying the reliability (r_j), release risk (w_j) and redundancy (m_j) factors for such an analysis are formidable, although this difficulty will be faced by most conceivable optimization schemes which address waste management realistically. This work must be accepted as an exercise in successive refinement over a long time of waste handling experience and analysis.

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APPENDIX A

COMPOSITION AND CALCULATION OF FIXED CHARGE RATE

APPENDIX A

COMPOSITION AND CALCULATION OF FIXED CHARGE RATE⁽¹⁾

The fixed charge rate for depreciable capital expenses, L_D , is calculated as follows:

$$L_D = \frac{k_y - (k_m/V_p) \sum_{n=1}^m P_n D_n}{(1 - k_e) K}$$

For non-depreciable capital expenses (land, etc.), the fixed charge rate, L_N , is calculated as follows:

$$L_N = \frac{k_h}{(1 - k_e) K}$$

The definition of the various symbols is given in Table A-1. For example, using the assumptions given below:

- m = 15 years project life
- b = 0.30 fraction in bonds
- i_e = 0.16 return on equity (after taxes)
- i_b = 0.05 interest on bonds
- k_a = 0.0035 (interim replacements factor)
- k_b = 0.0025 (property insurance factor)
- k_p = 0.032 (property tax on working capital)
- k_r = 0.00 (gross revenues tax)
- k_s = 0.03 (state income tax)

- $k_t = 0.50$ (Federal income tax)
- $k_v = 0.032$ (property tax)
- Sum of years' digits depreciation method, no investment credit

the L_D and L_N fixed charge rates are:

$$L_D = 24.04\%$$

$$L_N = 28.04\%$$

TABLE A-1. Definition of Various Terms in Fixed Charge Rate Calculation⁽¹⁾

- b = fraction of investment in bonds; $(1-b)$ fraction of investment in equity
- D_n = depreciation allowance for tax purposes in year n , dollars
- i_b = bond interest
- i_e = earning rate on equity after taxes
- $i_{vs} = (1 - b)i_e + (1 - k_m)bi_b$

The constants k_y, k_m, k_e , and k_h are calculated from the following input parameters:

- k_a = interim replacements factor,
- k_b = property insurance rate,
- k_p = property tax rate on working capital,
- k_r = state gross revenues tax rate,
- k_s = state income tax rate,
- k_t = Federal income tax rate,
- k_v = property tax rate.

The equations used for these calculations are as follows:

$$k_m = k_t + (1 - k_t)k_s,$$

$$k_d = (1 - k_s)(k_b + k_p),$$

$$k_w = 1 - (1 - k_r)(1 - k_s),$$

$$k_e = k_t + (1 - k_t)k_w,$$

$$k_h = 1 - p_m + (1 - k_t)k_d K,$$

$$k_y = 1 + (1 - k_t) \left[K(1 - k_s)(k_a + k_b) + k_v(1 - k_s) \sum_{n=1}^m p_n \left(\frac{m+1-n}{m} \right) \right]$$

K = uniform series present-worth factor, given by

$$K = \frac{(1 + i_{vs})^m - 1}{i_{vs}(1 + i_{vs})^m},$$

L_D = fixed charge rate on depreciable capital,

L_N = fixed charge rate on non-depreciable capital,

m = project lifetime for economic purposes, years,

p_n = present-worth factor for year n, equal to $(1 + i_{vs})^{-n}$,

V_p = total depreciable investment, dollars,

APPENDIX B

OUTLINE OF CALCULATION PROCEDURE FOR VARIOUS CLAD WASTE MANAGEMENT STEPS

APPENDIX B

OUTLINE OF CALCULATION PROCEDURE FOR VARIOUS CLAD WASTE MANAGEMENT STEPS

DENSIFICATION

For this order of magnitude estimation, the following assumptions are made for the densification step:

- 9 in. diameter briquettes/ingots for the die-compacted and ingot forms
- work load is 50% of desired equipment capacity
- 8 hr/day for densification; remainder of shift time for maintenance and preparation
- direct capital cost items to include:
 - equipment (mill, press, furnace, etc.)
 - equipment related controls/instrumentation
 - remote maintenance building requirement
 - contact maintenance building requirement
 - miscellaneous equipment
 - installation (turn-key pricing)
 - a backup facility will double all direct costs except the contact maintenance building (control center)

Equipment Capacity:

The desired equipment capacity (EC_x) may be expressed,

$$\begin{aligned} EC_x &= [\text{tons CW/GWe/yr}] \times L \times [\text{GWe(rated)}] / 365 \times 8 \times 0.5 \\ &= 6.85 \times 10^{-4} \times [\text{tons CW/GWe/yr}] \times L \times [\text{GWe}] \quad (\text{tons/hr}) \end{aligned} \quad (B-1)$$

where L is the load factor. The first bracketed term is the clad waste generation rate corresponding to a given reactor type, burnup, clad waste model. Values of this factor for the Diablo Canyon and Reference Fuel Assembly models, together with volume generation rates corresponding to various degrees of densification are given in Table B-1.

TABLE B-1. Clad Waste Weight and Volume Generation Rates
for LWR(U) Reactor Economy at 33 GWd/MT, 32.5% Eff. (5)

Clad Waste Model	Form	Bulk Density (gm/cm ³)	Volume Rates		Weight Rates	
			(m ³ /MTU)	(m ³ /GWe/yr)	(MT/GWe/yr)	(tons[short]/GWe/yr)
DC ^(a)	uncomp.	1.2	2.3-1 ^(c)	7.8	9.2	1.0 + 1
DC	rolled	3.3	8.2-2	2.8	9.2	1.0 + 1
DC	die-comp.	4.5	6.0-2	2.0	9.2	1.0 + 1
DC	ingot	6.5	4.2-2	1.4	9.2	1.0 + 1
RFA ^(b)	uncomp.	1.0	3.3-1	1.1 + 1	1.1 + 1	1.2 + 1
RFA	rolled	3.4	9.7-2	3.3	1.1 + 1	1.2 + 1
RFA	die-comp.	4.6	7.0-2	2.4	1.1 + 1	1.2 + 1
RFA	ingot	6.6	4.9-2	1.7	1.1 + 1	1.2 + 1

(a) Diablo Canyon Model

(b) Reference Fuel Assembly Model

(c) 2.3-1 = 2.3×10^{-1} , etc.

Equipment Cost

Let $E\$_x$ be the desired equipment cost, $E\$_r$ be a reference equipment cost, EC_x and EC_r be the corresponding capacities. Using the following scaling assumption,⁽¹³⁾

$$E\$_x = E\$_r \times (EC_x/EC_r)^{0.6}$$

and using (B-1), $E\$_x$ may be expressed,

$$E\$_x = E\$_r (6.85 \times 10^{-4} \times [\text{tons/GWe/yr}] \times L \times [\text{GWe}]/EC_r)^{0.6} \quad (\text{B-2})$$

$$\text{Let } E\$_r = 200,000 \times (\rho/4.5)^{0.6} \quad (\text{B-3})$$

where

200,000 is the cost of a press for 5 tons/hr capacity⁽⁶⁾

4.5 is the reference density (die-compacted)

ρ is the target density ($3.3 \leq \rho \leq 6.5$)

0.6 is the scaling factor for equipment cost

The equipment cost ($E\$_x$) may then be expressed,

$$E\$_x = 200,000 \times (\rho / 4.5)^{0.6} \times (6.85 \times 10^{-4} \times [\text{tons / GWe/yr}] \times L \times [\text{GWe}] / EC_r)^{0.6} \quad (\text{B-4})$$

Building Cost

$$\text{Let } A_r = 750 \times (\text{actual throughput} / 1.1 \times 10^{-1})^{0.4}$$

where

A_r is the desired remote building floor area,

750 is the remote floor area requirement (ft^2) for a throughput corresponding to 20 GWe (1.1×10^{-1} tons/hr) (see equation B-1)

0.4 is the scaling factor for the remote maintenance area

$$\text{Let } A_c = 400 \times (\text{actual throughput} / 1.1 \times 10^{-1})^{0.2}$$

where

A_c is the desired contact building floor area

400 is the contact floor area for throughput corresponding to 20 GWe

0.2 is the scaling factor for the contact maintenance area

Let F be a multiplier of direct equipment cost to account for: (a) instrumentation and controls ($F_{i/c}$); (b) miscellaneous equipment (F_{misc}); (c) installation (F_{inst}). Let A and H be the floor area and height, respectively, for remote (r) and contact (c) maintenance buildings associated with the given step (densification). $V\$$ is the construction cost of the buildings on a volume basis ($\$/\text{unit volume}$). Using these

abbreviations, the total direct capital cost for the densification equipment may be expressed:

$$CAPD_{dens} = E\$_x (1 + F_{i/c} + F_{misc} + F_{inst}) + A_c H_c V\$_c + A_r H_r V\$_r \quad (B-5)$$

for a single densification line. For a backup line (see above assumptions),

$$CAPD_{dens(backup)} = 2 \times CAPD_{dens} - A_c H_c V\$_c \quad (B-6)$$

The following size and cost data were used in this order of magnitude calculation of densification power cost effect:

<u>Item</u>	<u>Ref.</u>
$E\$_r$: \$200,000 (die-compaction press, $EC_r = 5$ ton/hr)	(6)
$F_{i/c}$: 0.3 (estimated from repro. plant costs)	(2)
F_{misc} : 0.5 (estimated from repro. plant costs)	(2)
F_{inst} : 0.11 (estimated from repro. plant costs)	(2)
H_c : 30 ft	(2)
$V\$_c$: 25\$/ft ³	(2)
H_r : 60 ft	(2)
$V\$_r$: 35\$/ft ³	(2)

$CAPD_{dens.}$ is computed using (B-4), (B-5) and B-6), and the clad waste generation rate data of Table B-1. $CAPD_{dens.}$ is substituted into formula (1b) of the text (neglecting the discount factor for this appraisal), to obtain the power cost effect (mills/kWh) for a given power level. Sample cost ($CAPD$) data are given for the 20 and 55 GWe power levels in Table B-2. Power cost effect data ($\Delta\$_{den}$) for the range of power levels considered in this review (5-1400 GWe) are given in Table 5 of the text.

CANNING

The can is the first stage containment for the clad waste. The number of cans/yr is calculated as follows:

$$\text{cans/yr} = \frac{[\text{MT CW/GWe/yr}] \times [\text{GWe}] \times L \times 10^3}{\text{can capacity(kg)}} \quad (\text{B-7})$$

Blomeke and Perona⁽⁶⁾ considered 9 in. and 24 in. inside diameter, mild steel cans, 10 ft long, filled to 8 ft. Using their can cost data: \$464/can for 24 in. and \$183/can for 9 in., and bulk density data from Table B-1, the can/yr and can cost/yr data are given below for the 20 GWe and 55 GWe power at levels at 80% L.

Form	GWe	24 In. OD Can			9 In. OD Can		
		Wgt/can (kg)	Cans/yr	Cost/yr (\$)	Wgt/can (kg)	Cans/yr	Cost/yr (\$)
Uncomp.	20	927	159	7.38 + 4	-	-	-
Rolled		2320	63	2.92 + 4	-	-	-
Die-Comp.		-	-	-	455	323	5.91 + 4
Ingot		-	-	-	650	226	4.14 + 4
Uncomp.	55	927	436	2.02 + 5	-	-	-
Rolled		2320	175	8.12 + 4	-	-	-
Die-Comp.		-	-	-	455	890	1.63 + 5
Ingot		-	-	-	650	623	1.14 + 5

Cost/yr represents CAPD for the canning step. These data are used in formula (1c) to obtain the power cost effect of canning for this appraisal. As a result of the analysis by Blomeke and Perona,⁽⁶⁾ only 24 in. cans were considered feasible for the uncompacted and rolled forms, while a 9 in. can was used for the die-compacted form. For this study, a 9 in. can is assumed for the ingot form as well. Power cost effect data for these conditions are given in Table 4 of the text.

TRANSPORTATION

The transportation cost depends on: (a) unit cask cost; (b) number of casks required for reasonable shipping schedule; (c) freight and handling costs; (d) roundtrip distance assumption. The various components of the transport cost are as follows:

- cask cost (shield material) = $[\# \text{ casks}] \times (W_{sh}) \times [\$/\text{lb shield}]$
- freight cost = $[(W_{cask}) \times [\$/\text{lb full}] + (W_{sh}) \times [\$/\text{lb empty}]] \times [\text{casks/yr}]$ (B-8)
- handling cost = $[\text{cans/cask}] \times [\text{casks/yr}] \times [\$/\text{can}] + [\# \text{ trips}] \times [\$/\text{trip}]$

Blomeke and perona⁽⁶⁾ used a computer code⁽⁷⁾ to design the shipping cask, taking cognizance of the thermal power and radiation (neutron, gamma) hazard of the clad waste. Setting clad waste centerline and base of cooling fin temperature criteria for normal and "standard fire" conditions, the code computes the overall cask dimensions, including the shield material and the cooling fins for a given weight of clad waste of a given age and composition. If W_{cask} is defined as the filled cask weight, W_{CW} is the contained weight of clad waste, and ρ is the bulk density of the clad waste, the following linear relationship appears to give a good correlation with Blomeke and Perona's data over a wide range of W_{cask} :

$$\log W_{CW} = m W_{cask} + n\rho + p \quad (\text{B-9})$$

i.e., for clad waste of a given age (post-reactor discharge time) and composition (model), the log of W_{CW} gives a reasonably good linear plot against W_{cask} , with a slope of m , and an intercept of $(n\rho + p)$.

Using the following units, convenient to this particular calculation: $W_{CW}(\text{kg})$, $W_{cask}(\text{tons})$, $\rho(\text{g/cm}^3)$, the parameters for equation (B-9) yielded by Blomeke and Perona's data are as follows for the various forms of clad waste:

<u>Form</u>	<u>ρ</u>	<u>m</u>	<u>n</u>	<u>p</u>
Uncomp.	1.2	7.41-3	0.183	2.48
Rolled	3.3	7.57-3	0.183	2.48
Die-Comp.	4.5	7.00-3	0.183	2.48
Ingot	6.5	7.33-3*	0.183	2.48

* Average value used for ingot form

For a given cask weight (W_{cask}) limit, formula (B-9) is used to compute the clad waste weight (W_{CW}) corresponding to a given density (ρ). Knowing the can capacity, the number of cans per cask is obtained (a fact which may be useful if certain geometrical constraints [not considered here] are operative). The shield weight (W_{shield}) is the difference between W_{cask} and W_{CW} , neglecting the weight of the cans. Following Blomeke and Perona's limit of 100 tons (short) for the cask weight (W_{cask}), the following sample data pertaining to the shipping cask requirements for the 20 and 55 GWe levels were obtained:

<u>GW</u>	<u>Clad Waste Form</u>	<u>Can</u>	<u>Clad Weight Can (lbs)</u>	<u>Cans/ Cask</u>	<u>W_{CW} (lb)</u>	<u>W_{shield} (lb)</u>	<u>W_{cask} (lb)</u>	<u>No. Casks</u>	<u>Casks/ Yr</u>	<u>No. Trips/ Yr</u>
20	Uncomp.	24"	2.04+3	3	6.08+3	1.94+5	2.00+5	2	53	29
	Rolled	24"	5.13+3	3	1.53+4	1.85+5	"	1	21	22
	Die-Comp	9"	1.01+3	22	2.21+4	1.78+5	"	1	15	16
	Ingot	9"	1.44+3	39	5.55+4	1.45+5	"	1	6	6
55	Uncomp.	24"	2.04+3	3	6.08+3	1.94+5	"	5	147	31
	Rolled	24"	5.13+3	3	1.53+4	1.85+5	"	2	58	35
	Die-Comp	9"	1.01+3	22	2.21+4	1.78+5	"	2	43	32
	Ingot	9"	1.44+3	39	5.55+4	1.45+5	"	1	16	17

The number of casks to be purchased for a given clad waste form was estimated as follows:

- assuming 40 mph average speed, 48 hours loading/unloading time, a 2000 mile round trip would take about 98 hours; while this would allow about seven single train trips per month, for safety/security reasons limit number of trips per month to 3, or 36/yr; the minimum number of casks per shipment is;

$[\# \text{ casks}]_{\min} = [\text{casks/yr}]/36$, using the next highest whole number

where the $[\text{casks/yr}] = [\text{wgt CW/GWe/yr}] \times [\text{GWe}] \times L/W_{\text{CW}}$

(see Table B-1)

The trips per year were estimated by using the maximum number of casks per shipment within the three shipment per month limit. Residual shipments, using progressively fewer casks, to satisfy the yearly total of casks were then distributed on a monthly, or yearly, basis to make up the total number of shipments. Some of these data are given in the data summary above. These assumptions leading to number of casks required and trips per year are independent of any made by Blomeke and Perona.⁽⁶⁾ If there is substantial disagreement in these respects, the close agreement in power cost effect of the transportation component between these calculations and those of Blomeke and Perona (see Table 3) must be attributed to compensating assumptions in the two calculations.

The following cost data from Blomeke and Perona⁽⁶⁾ were used in estimating the transport cost for the various clad waste forms (see relationships B-8).

- $[\$/1\text{b shield}] = 2.00$ (iron)
- $[\$/1\text{b full}] = 0.0265$
- $[\$/1\text{b empty}] = 0.0185$
- $[\$/\text{can}] = 80$
- $[\$/\text{trip}] = 1,000$

Using the above calculation procedure and cost assumptions, the power cost effect data for the transportation component ($\Delta\$_{tr}$) were computed using formula (1b) of the text. These data are summarized in Table 5 for the full range of power levels considered.

DISPOSAL

The salt disposal technique used by Blomeke and Perona⁽⁶⁾ consists of a 250 net acre (mine floor area) disposal facility at a 1000 ft depth. The 10 ft cans are disposed vertically in holes whose depth allows about 5 ft of crushed salt as a cover. A cost of 106×10^6 \$ (1970) was used for a facility of 20-year active life. This figure includes construction, operation, maintenance, and a \$500,000 perpetual maintenance fund at end of active life. For 250 net acres, this amounts to $\$9.90/\text{ft}^2$ of net area.

The disposal cost per can is calculated as follows:

$$[\text{cost/can}] = \frac{[\text{thermal power/can (W)}] \times [\text{cost}/\text{ft}^2 \text{ net area}]}{[\text{limiting areal thermal power density (W}/\text{ft}^2)]}$$

Based on ORNL heat transfer analysis referenced by Blomeke and Perona,⁽⁶⁾ which limits salt temperature to about 200°C, the subject clad waste is given an areal power density rating of $22 \text{ W}/\text{ft}^2$ of net mine area. Substituting the given values in the above relationship,

$$[\text{cost/can}] = \frac{[\text{thermal power/can (W)}] \times \$9.90/\text{ft}^2}{22 \text{ W}/\text{ft}^2}$$

The subject clad waste of one-year age (post reactor discharge time) has a thermal power loading of about 0.57 W/kg.^(5,6) The following table gives data pertinent to the disposal cost calculation for the various clad waste forms considered.

Form	Can Size (OD, in.)	Weight/Can (kg)	Power/Can (W)	Disposal Cost/Can (\$)	Net Area/ GWe/yr (ft ²)
Uncomp.	24	927	528	300 (minimum)	2.38×10^2
Rolled	24	2320	1320	600	2.38×10^2
Die-Comp.	9	455	260	300 (minimum)	2.38×10^2
Ingot	9	650	372	300 (minimum)	2.38×10^2

The number of cans for disposal per year is computed from formula B-7, using clad waste output data from Table B-1, a reactor load factor of 80%, and the can loadings given above. With the unit disposal cost data of the above table, the yearly disposal cost is computed. This figure is used in formula (1c) of the text to estimate the power cost effect of the given disposal operation.

As noted in the above table, the net disposal area per GWe/yr is independent of the clad waste density if a constant areal power density (W/ft^2) is assumed for all densities. This is shown as follows:

$$\begin{aligned} \text{net area/GWe/yr} &= \frac{[W/kg] \times [kg/can] \times [kg \text{ CW/GWe/yr}]}{[W/ft^2] \times [kg/can]} \\ &= \frac{[W/kg] \times [kg \text{ CW/GWe/yr}]}{[W/ft^2]} \end{aligned}$$

For the present clad waste, the net area/GWe/yr computes as follows:

$$\text{net area/GWe/yr} = 0.57 \times 9.2 \times 10^3 / 22 = \underline{2.38 \times 10^2 \text{ ft}^2/\text{GWe/yr}}$$

With clad waste of one-year age, the 245 net acre disposal facility will exceed the capacity required for all of the installed power levels considered in this appraisal, over the 20-year active life assumed for the facility. For example, at 80% load factor, the 5 and 1400 GWe levels will require 0.44 and 124 acres, respectively, over a 20-year period.

SUMMARY

Cost data are summarized in Table B-2 for the 20 and 55 GWe installed power levels. Cost data for the other power levels are easily derived from formula (1b), using the power cost effect data given in the text for the various steps.

Other scaling laws for equipment, building space, etc., have been proposed (e.g., 1, 3, 11) and certainly cost data are sensitive to the period of the analysis and the projection time. While the power cost effect data of this appraisal apply to roughly the period 1970-1973, it is not expected that more contemporary cost and FRC data would markedly affect the relative power cost effect of clad waste management identified in this order of magnitude appraisal.

TABLE B-2. Summary of Cost (CAPD) Data for Various
Clad Waste Management Steps

[LWR(U) reactor; 33 Gwd/MT; 80% Load Factor
Diablo Canyon Clad Model; 1-year age

GWe	Form	\$ (Densification)	\$ (Canning)	\$ (Transportation)	\$ (Disposal)	Σ\$
20	Uncompacted	0	0 ^(a)	7.38+4 ^(b)	1.29+6	4.77+4
	Rolled	1.90+6	3.50+6	2.92+4	5.78+5	3.78+4
	Die-Comp.	1.92+6	3.54+6	5.91+4	4.81+5	9.69+4
	Ingot	1.92+6	3.54+6	4.14+4	3.43+5	6.78+4
55	Uncompacted	0	0	2.02+5	3.32+6	1.31+5
	Rolled	2.81+6	5.24+6	8.12+4	1.29+6	1.05+5
	Die-Comp.	2.82+6	5.28+6	1.63+5	1.03+6	2.67+5
	Ingot	2.84+6	5.28+6	1.14+5	4.83+5	1.87+5
						1.41+6
						1.41+6 ^(a)
						2.55+6
						4.15+6
						2.56+6
						4.18+6
						2.37+6
						3.99+6
						3.65+6
						3.65+6
						4.29+6
						6.72+6
						4.28+6
						6.74+6
						3.62+6
						6.06+6

(a) Refers to backup densification case.

(b) $7.38 + 4 = 7.38 \times 10^4$, etc.

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