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BNWL-2104

UC-70

A Brief Assessment of Some Technical and Radiological Hazard Factors Affecting Clad Waste Management

by
G. E. Zima

July 30, 1976

**Prepared for the Energy Research
and Development Administration
under Contract E(45-1)-1830**

Battelle
Pacific Northwest Laboratories

BNWL-2104

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Under Contract E(45-1)-1830

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$5.50; Microfiche \$2.25

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CLAD WASTE MANAGEMENT

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CONTENTS

1.0	INTRODUCTION	1
2.0	RELATIVE IMPORTANCE OF VARIOUS NUCLEAR FUEL WASTE STREAMS	3
3.0	SPENT FUEL RADIOACTIVITY AND RADIOLOGICAL HAZARD BURDENS.	5
4.0	COMPARISON OF VARIOUS INDICES FOR HIGH LEVEL WASTE AND CLAD WASTE.	9
4.1	Volume Comparison for Various Densification Levels	9
4.2	Radioactivity Comparison.	14
4.3	Radiological Hazard Comparison.	21
4.4	Thermal Power Comparison.	27
5.0	COMPARISON OF RADIOACTIVITY AND THERMAL POWER OF CLAD WASTE FOR REFERENCE FUEL ASSEMBLY AND DIABLO CANYON FUEL MODELS.	31
6.0	SOME TECHNICAL MEASURES OF THE WASTE MANAGEMENT PROBLEM OF CLAD WASTE RELATIVE TO HIGH LEVEL WASTE	33
7.0	CONCLUSION	35
8.0	REFERENCES	37

A BRIEF ASSESSMENT OF SOME TECHNICAL AND RADIOLOGICAL HAZARD FACTORS AFFECTING CLAD WASTE MANAGEMENT

G. E. Zima

1.0 INTRODUCTION

Demonstration of a practicable management strategy for the principal predictable adverse by-products of nuclear energy, namely, the waste from mining, milling, fuel manufacture, reactor operations and fuel reprocessing, appears to be a prime impediment to general public acceptance of the nuclear energy source. Although all of the above phases of the nuclear energy process pose problems in minimizing the public hazard, the general problem is centered in the post-reactor discharge phases where there is a concentration of radioactive products within a broad spectrum of physico-chemical forms, a need to transport these products among the various sites pertaining to the nuclear fuel process/cycle, and a need for ultimate disposal of certain products which must recognize a public hazard span greater than several hundred thousand years.

The throwaway strategy of nuclear fuel management is wasteful of energy resources, both potential and expended. Assuming minimal destruction of the spent fuel assembly, it does, however, provide the most compact "natural" form for the spent fuel products. It also provides the highest radioactivity and thermal power densities, characteristics which are at some opposition to compactness with respect to the overall waste handling problem. With conservation of fissile products, various waste streams are generated in the reprocessing and fuel manufacturing plants which add both volume and physico-chemical diversity to the subjects of the nuclear fuel waste management problem. Of these streams, the so-called high level waste (HLW) and the clad waste streams carry the principal radiological hazard and thermal power burdens when considering post reactor-discharge times in excess of roughly a year and reasonable contamination factors.

The specifics of the waste management problems associated with these two streams are dependent on the reactor type, the fuel type, the burnup, and in-reactor neutron flux distribution and history, the post-reactor discharge time, and the physico-chemical state imparted to the harmful components of the waste by the reprocessing and manufacturing operations specific to the waste.

In attempting to gain some measure of the relative importance of the high level and clad waste streams within the context of a reasonable nuclear power scenario, various technical and hazard indices are compared for the light water, enriched uranium fueled, reactor [LWR(U)]. For the clad waste, two fuel models are used for the volume comparison, namely, the Reference Fuel Assembly (RFA) and the Diablo Canyon reference fuel model (DC). The more extensive data available for the Diablo Canyon model on radioactivity and thermal power are used in the comparison of these indices. Most of this review pertains to a burnup of 33GWD/MT because of the predominance of this particular burnup in waste management literature. A brief analysis is given of the effect of burnup and fuel model on certain clad waste characteristics.

The clad waste management problem will involve a number of factors, including: operational and public hazard analysis of all phases of clad waste handling and storage; justification and feasibility analysis of decontamination, densification, and useful product manufacture; the establishment of criteria for acceptable storage forms for clad waste over the time span bracketed by reactor discharge and ultimate disposal. Technico-economic analysis and progressive optimization are fundamental to the evolution of candidate waste management strategies for public appraisal. This report is submitted as a preliminary to technico-economic considerations of clad waste which are within the current responsibility of the Materials Department of the Pacific Northwest Laboratories

2.0 RELATIVE IMPORTANCE OF VARIOUS NUCLEAR FUEL WASTE STREAMS

In a recent general review article on nuclear fuel waste management, Wolfe⁽¹⁾ gives a fuel cycle waste projection for the year 2000, based on a previous nuclear power scenario.⁽²⁾ His summary is given in Table 1, which lists volume and radioactivity for various waste categories on annual and accumulation bases. These waste categories closely follow those given by Blomeke et al.⁽³⁾ Considering the gross radioactivity (MCi), it is obvious that the high level waste dominates the waste problem. From a volume standpoint, that of the high level waste is trivial compared to a number of other, less dangerous, categories. The radioactivity of the clad waste on both annual and accumulation bases is roughly "equivalent" to the noble gases. As shown later, however, this comparison is strongly sensitive to the post-reactor discharge time and the assumed fission product and transuranics contamination of the clad waste. Furthermore, the radiological hazard is of greater significance than the gross radioactivity.

On the basis of the long range radiological hazard index, to be discussed later, the transuranics and fission products (excluding the noble gases, tritium and iodine isotopes) dominate the waste management problem. It is appropriate, therefore, to concentrate the following discussion on the two waste streams that will, collectively, carry the greatest burden in this respect under reasonable contamination assumptions, namely, the high level waste and the clad waste streams.^(4,5)

The nuclear power projection used by Wolfe⁽¹⁾ assumes a mix of various reactor types. One such mix given in his forecast source⁽²⁾ is as follows for the year 2000:

<u>Type</u>	<u>% of Total Installed Capacity</u>
LWR(PWR)	51.0
LWR(BWR)	24.8
HTGR	9.6
FBR	14.6

Plutonium recycle is assumed to begin near the year 1980.

TABLE 1. Fuel Cycle Wastes Projected for the Year 2000⁽¹⁾

Waste Category	Annual Generation		Accumulated Inventory		Metric Tons of Transuranics
	Volume (10 ³ ft ³)	Activity (MCi)	Volume (10 ³ ft ³)	Activity (MCi)	
<u>High-level Solidified</u>	49	57,800	470	158,000	1,360
<u>Transuranium Wastes</u>					
cladding hulls	52	230	440	860	93
misc. alpha, beta, gamma solids	340	6.7	3,000	27	0.6
alpha solids	1,140	31	8,600	170	19
<u>Beta-Gamma Wastes</u>					
noble gases	2.4	230	21	1,500	0
iodine	0.08	0.0008	0.7	0.007	0
LWR tritium	-		25,000	2.3	0
FP tritium	9.3	14	85	92	0
misc. beta, gamma solids	36,900	3.8	260,000	1.9	0
<u>Ore Tailings</u>	1,600,000	0.5	21,300,000	6.9	98,300

In the following discussion, the comparison of the high level waste and the clad waste is given as a function of the post-reactor discharge time (hereinafter abbreviated as Θ). Use of the time since discharge (generation) from the reprocessing plant as the time reference is common.^(e.g.3) This particular formality requires a further specification of the time interval between reactor discharge and reprocessing for decay calculations, a possibly variable factor whose significance lies chiefly in the identification of the time of the physico-chemical transformation of the waste forms effected by reprocessing.

3.0 SPENT FUEL RADIOACTIVITY AND RADIOLOGICAL HAZARD BURDENS

The spent fuel burden of the various fission derivatives is a logical base from which to consider the post-reactor discharge waste management problem. Table 2 presents gross radioactivity data for the various nuclide classes comprising the radioactivity burden of the spent fuel. Data are given on a MTU (metric ton of uranium charged to reactor) basis as a function of the post-reactor discharge time (θ). The table also gives the relative importance (% of total) of the various nuclide classes. On a gross radioactivity basis, the fission products (FP's) dominate up to some point between 100 and 1000 years, the transuranics (TRU's) constituting the major balance over this interval and dominating out to roughly 10^5 years, beyond which point uranium isotopes increase in radiological significance (e.g., about 96% by 10^6 years). Data for this particular reactor system [LWR(U) reactor, Diablo Canyon fuel model, 33 MWD/MT burnup] were obtained from reported ORIGEN code calculations,^(3,6) correcting for uranium and plutonium depletion where necessary for the long term data.⁽⁶⁾ Long term light metal (LM) data were obtained by calculating decay constants for the principal long term LM's from short term data⁽³⁾ (^{55}Fe , ^{60}Co , ^{59}Ni , ^{93}Zr , ^{121}M Sn, ^{135}Sb , ^{125}M Te).

Table 3 presents the air radiological hazard index for the various nuclide classes as a function of θ . The individual class radiological hazard index is defined as the aggregate of the volume (m^3) of air, or water, needed to bring the maximum permissible concentration (MPC) of the nuclides within the class to the level specified in 10 CFR 20.⁽⁷⁾ The overall radiological hazard index (sum over all nuclide classes) is given at the right side of the table. The lower portion of the table gives the relative importance (% of total) of the various classes as a function of θ . In contrast to Table 2, it is noted that on the basis of the more significant radiological hazard index, the TRU's dominate from the outset of reactor discharge and constitute virtually 100% of the radiological hazard beyond roughly 100 years. MPC data were obtained from the latest source⁽⁷⁾ for individual nuclides and the radiological hazard index for a given nuclide class was obtained by computing the radiological hazard

index for each nuclide within the class, using radioactivity data from sources previously cited.^(3,6) The relative importance data are plotted against Θ in Figure 1.

TABLE 2. Spent Fuel Radioactivity Burden for Various Nuclide Classes

LWR (U) Reactor
33GWD/MT Burnup, 2.92×10^{13} n/cm² sec flux
Diablo Canyon Fuel Model

$\Theta(\text{yr})$	Noble Gases	<u>Ci/MTU</u> ^(a)					
		³ H	I	FP's	TRU's	LM's	$\Sigma \text{Ci/MTU}$
0.4	1.63×10^6 ^(b)	6.92×10^2	8.61×10^5	1.36×10^8	3.91×10^7	1.42×10^5	1.78×10^8
1.4	1.06×10^4	6.54×10^2	3.75×10^2	2.21×10^6	1.14×10^5	1.00×10^4	2.35×10^6
10.4	5.96×10^3	3.94×10^2	3.75×10^2	3.12×10^5	7.20×10^4	2.4×10^3	3.93×10^5
100	1.81×10^1	2.47	3.75×10^2	3.42×10^4	1.39×10^4	2.68×10^2	4.81×10^4
1000	1.50×10^{-24}	2.35×10^{-22}	3.75×10^2	2.09×10^1	2.21×10^3	4.24	2.23×10^3
10000			3.75×10^2	1.99×10^1	1.52×10^3	3.95	1.54×10^3

Relative Radioactivity Importance of Various Nuclide Classes (% of Total)
(%)

0.4	9.2×10^{-1}	3.9×10^{-4}	4.8×10^{-1}	7.6×10^1	2.2×10^1	8.0×10^{-2}
1.4	4.5×10^{-1}	2.8×10^{-2}	1.6×10^{-6}	9.4×10^1	4.9	4.3×10^{-1}
10.4	1.5	1.0×10^{-1}	9.6×10^{-6}	8.0×10^1	1.8×10^1	6.1×10^{-1}
100	3.8×10^{-2}	5.1×10^{-3}	7.8×10^{-5}	7.1×10^1	2.9×10^1	5.6×10^{-1}
1000	-	-	1.7×10^{-3}	9.4×10^{-1}	9.9×10^1	1.9×10^{-1}
10000	-	-	2.4×10^{-3}	1.3	9.9×10^1	2.6×10^{-1}

a. Noble gases: ⁸⁵Kr, ^{131m}Xe, ¹³³Xe

Iodine Isotopes: ¹²⁹I, ¹³¹I

Fission Products (FP's): all except noble gases, iodine

b. $1.63 \times 10^6 = 1.63 \times 10^6$

$1.50 \times 10^{-24} = 1.50 \times 10^{-24}$, etc.

TABLE 3. Spent Fuel Radiological Hazard Index for Various Nuclide Classes (Air)

[LWR (U) Reactor
33GWD/MT Burnup, 2.92×10^{13} n/cm²/sec flux]
Diablo Canyon Fuel Model]

$\Theta(\text{yr})$	Noble Gases	³ H	$(\text{m}^3/\text{MTU})_{\text{air}}(\text{a})$				$\Sigma(\text{m}^3/\text{MTU})_{\text{air}}$
			I	FP's	TRU's	LM's	
0.4	3.7×10	3.6×9	8.6×15	1.9×16	1.1×17	9.1×13	1.4×17
1.4	3.3×10	3.3×9	1.9×9	5.9×15	3.1×17	1.9×13	3.2×17
10.4	1.9×10	2.0×9	-	2.3×15	3.4×17	6.0×12	3.4×17
100	5.9×7	1.2×7	-	2.3×14	1.9×17	1.3×11	1.9×16
1000	-	-	-	8.2×9	3.6×16	3.6×8	3.6×16
10000	-	-	-	8.0×9	2.5×16	2.2×8	2.5×16

Relative Importance of Radiological Hazard of Various Nuclide Classes (Air)
(% of Total)

0.4	2.7 - 5	2.6 - 6	6.2	1.4 + 1	8.0 + 1	6.6 - 2
1.4	1.0 - 5	1.0 - 6	6.0 - 7	1.9	9.8 + 1	6.0 - 3
10.4	5.6 - 6	5.8 - 7	5.6 - 7	6.7 - 1	9.9 + 1	1.8 - 3
100	3.1 - 8	6.3 - 9	1.0 - 6	1.2 - 1	$\sim 1.0 \times 2$	6.8 - 5
1000	-	-	5.3 - 6	2.3 - 5	$\sim 1.0 \times 2$	1.0 - 6
10000	-	-	7.6 - 6	3.2 - 5	$\sim 1.0 \times 2$	8.8 - 7

a. m^3 refers to air volume needed to bring nuclide concentration to MPC as specified in Ref. 7. The lowest MPC value of Ref. 7 was used for each nuclide in computing volume.

FIGURE 1. Relative Importance (% of Total) of Radiological Hazard of Various Nuclide Classes of Spent Fuel Versus Post-Reactor Discharge Time

4.0 COMPARISON OF VARIOUS INDICES FOR HIGH LEVEL WASTE AND CLAD WASTE

4.1 VOLUME COMPARISON FOR VARIOUS DENSIFICATION LEVELS

In assessing clad waste characteristics, assumptions must be made as to the allotment of the various metallic components of the fuel assembly to the clad waste (i.e. the disassembly and sorting operations prior to the chop-leach phase which "generates" the clad waste) and as to the pre-reactor exposure chemical composition of the metals assigned to the clad waste [basic as well as tramp elements (such as uranium) with radiological significance]. The LWR's are expected to bear the major nuclear power load up to at least the year 2000 (see Section 2.0), with roughly a 2:1 proportion of PWR to BWR reactor types within the LWR segment of nuclear power. Two fuel (clad waste) models which have been proposed for characterization of the clad waste from LWR's, using either enriched uranium or plutonium recycle fuel, are the Diablo Canyon Reference Fuel Model^(3,4,5,8) and the Reference Fuel Assembly.⁽⁹⁾ The metallic (non-fuel) composition of these models is given in Table 4, together with the weight of clad waste per MTU (or MTHM) assigned to each model. The Zircaloy channels of the BWR fuel assemblies are excluded from the clad waste. The Diablo Canyon model represents essentially Zircaloy cladding (~93 w/o) and Inconel spacers (~7 w/o), while the Reference Fuel Assembly model includes some Type 304 stainless steel in a clad waste alloy mix comprised of Zr-4 (88.6 w/o), 304 SS (8.91 w/o), and Inconel-718 (2.45 w/o).

Densities, MTU specific volumes, and GWe-yr specific volumes are given in Table 5 for the Diablo Canyon (abbreviated as DC), the Reference Fuel Assembly (abbreviated as RFA) and the high level waste (abbreviated as HLW), for various forms of these wastes. Density and specific volume estimates were obtained from the table cited references.

Referring to the GWe-yr and MTU specific volume columns, the DC fuel model clad waste and the HLW are virtually equivalent on this basis for the die-compacted and vitriified forms, respectively.

Using the LWR nuclear power and fuel processing forecast given in ERDA-76-43,⁽¹¹⁾ the total volume for the various forms of HLW and clad waste (abbreviated as CW) are given in Table 6, using specific volume data given

TABLE 4. Metal (Non-Fuel) Compositions Assumed for Diablo Canyon and Reference Fuel Assembly Models for Clad Waste

Diablo Canyon Model⁽⁸⁾

<u>element</u>	<u>g/MT cladding</u>	<u>w/o</u>
carbon	66	0.0066
aluminum	399	0.0399
silicon	66	0.0066
titanium	664	0.0664
vanadium	27	0.0027
chromium	13,500	1.35
manganese	66	0.0066
iron	13,800	1.38
cobalt	200	0.02
nickel	35,280	3.53
niobium	3520	0.352
molybdenum	2100	0.210
tin	13,900	1.39
zirconium	9.2×10^5	92.0

(includes Inconel spacers/grids; assumes about 7 w/o Inconel)

271 kg clad waste/MTU

Reference Fuel Assembly Model⁽⁹⁾

<u>alloy</u>	<u>element</u>	<u>g/assembly</u>	<u>w/o^(a)</u>
Zr-4	Sn	1430	1.42
	Fe	202	6.74
	Cr	112	2.27
	Zr	87,850	87.0
Type 304 SS	Cr	1710	-
	Ni	811	2.10
	Mn	180	0.178
	Si	90	0.0891
	P	18	0.0178
	C	14	0.0149
	Se	14	0.0139
	S	5	0.0050
	Fe	6160	-
Inconel- 718	Ni	1310	-
	Cr	470	-
	Fe	446	-
	Nb/Ta	124	0.123
	Mo	74	0.0733
	Co	20	0.0198
	Ti	20	0.0198
	Al	15	0.0149
	C	1	-

325 kg Clad Waste/MTHM

a. First entry for element is sum for all entries of element

in Table 5. The extremes (high-low) in the volume forecast for the HLW and clad waste are plotted versus the year in Figure 2. It is seen that there is considerable overlap in the volume factor for the HLW and clad waste streams, depending on the particular forms of these wastes. As noted previously, with the clad waste in the die-compacted form⁽⁴⁾ and the HLW in the vitrified form,⁽¹⁰⁾ the GWe·yr specific volumes of these wastes are virtually equal, as reflected in columns 2 and 8 of Table 6.

TABLE 5. Specific Volume (MTU and GWe·yr Bases) for Various Waste Forms

<u>Waste</u>	<u>Form</u>	<u>g/cm³</u>	<u>m³/MTU</u>	<u>m³/GWe·yr^(a)</u>	<u>Reference</u>
CLAD (DC)	uncomp.	1.2	2.3 - 1	7.8	5
CLAD (DC)	rolled	3.3	8.2 - 2	2.8	5
CLAD (DC)	compacted	4.5	6.0 - 2	2.0	5
CLAD (DC)	ingot	6.5	4.2 - 2	1.4	5
CLAD (RFA)	uncomp.	1.0	3.3 - 1	1.1 + 1	9
CLAD (RFA)	rolled	3.4	9.7 - 2	3.3	Est. from Ref. 5 data
CLAD (RFA)	compacted	4.6	7.0 - 2	2.4	"
CLAD (RFA)	ingot	6.6	4.9 - 2	1.7	"
HLW	liquid conc.		3.8 - 1	1.3 + 1	9
HLW	calcine ^(b)		5.0 - 2	1.7	10
HLW	vitrified ^(c)		6.0 - 2	2.0	10
HLW	metal-HLW compact ^(d)		3.0 - 2	1.0	10

a. $m^3/\text{GWe}\cdot\text{yr} = m^3/\text{MTU} \times 34.03 \text{ (MTU/GWe}\cdot\text{yr)}$ [33 GWD/MT burnup, LWR(U)]

b. range for calcine = 0.04 - 0.06 m^3/MTU

c. range for vitrified = 0.04 - 0.08 m^3/MTU

d. range for metal-HLW compacts (molten metal casting, powdered metal sintering) = 0.03 - 0.08 m^3/MTU (low value used for table and plots)

TABLE 6. Total Volume Projection for HLW and Clad Waste

Year	MTU proc.	(a) <u>GWe(eff.)</u> <u>LWR(U)</u>	(b) Waste Type/Form								
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
			CW(DC)			CW(RFA)					
VOLUME (m ³)											
1979	1500	44.1	3.5+2	9.0+1	6.3+1	5.0+2	1.1+2	7.4+1	5.7+2	9.0+1	4.5+1
1984	3100	91.1	7.1+2	1.9+2	1.3+2	1.0+3	2.2+2	1.5+2	1.2+3	1.9+2	9.3+1
1989	5578	164.	1.3+3	3.4+2	2.3+2	1.8+3	3.9+2	2.7+2	2.1+3	3.4+2	1.7+2
1994	9314	274.	2.1+3	5.6+2	3.9+2	3.1+3	6.5+2	4.6+2	3.5+3	5.6+2	2.8+2
1999	13,268	390.	3.1+3	8.0+2	5.6+2	4.4+3	9.3+2	6.5+2	5.0+3	8.0+2	4.0+2

a. LWR(U) fuel processing projection from Ref. 11, based on installed capacity and load factor assumptions given in Ref. 3; 33 GWD/MT burnup

b. (1) - clad waste (DC), uncompacted (see Table 5 for m³/MTU assumptions)

(2) - clad waste (DC), die compacted

(3) - clad waste (DC), ingot

(4) - clad waste (RFA), uncompacted

(5) - clad waste (RFA), die compacted

(6) - clad waste (RFA), ingot

(7) - HLW, liquid concentrate

(8) - HLW, vitrified (0.06 m³/MTU assumed)

(9) - HLW, metal-HLW compact (0.03 m³/MTU assumed)

FIGURE 2. Total Volume Comparison for HLW and Clad Waste Versus Calendar Year for Various Forms of Waste

4.2 RADIOACTIVITY COMPARISON

Again using the LWR(U) reactor and the Diablo Canyon fuel model, the aggregate radioactivity burden for the HLW and clad waste streams are compared for the various nuclide classes in Table 7. The contamination assumptions for the HLW and clad waste are given at the bottom of the table. These have been used extensively in ORNL analysis of nuclear waste and are believed to represent fairly realistic conditions. Radioactivity is given for the various classes on a MTU basis and for the total on a GWe·yr basis as well. The aggregate data on a GWe·yr basis are plotted versus Θ in Figure 3 for the HLW and the clad waste.

Using the GWe·yr specific volume data given in Table 5 for the HLW and the clad waste, and the aggregate radioactivity data given in Table 7, radioactivity "densities" (MCi/m^3) were computed for these wastes for the densification extremes given in Table 5. These data are plotted in Figure 4 versus Θ . On a GWe·yr basis (Figure 3), it is seen that the HLW retains higher aggregate radioactivity burdens throughout the span of Θ . On a "density" basis (Figure 4), there is some overlap of the HLW and the clad waste bands, starting at about 10,000 years.

In view of the current Federal restrictions on transuranics (TRU's) contaminated waste, it is interesting to estimate the TRU's burden of the Diablo Canyon fuel model clad waste as a function of Θ for several TRU's contamination levels (percent of spent fuel TRU's burden in clad waste). These data are given in Table 8 for 0.1 and 0.05 w/o contamination levels (the latter value being used in the present HLW clad waste comparison). TRU's contamination is given in terms of nCi per gram of clad waste in Table 8. Table 9 gives the decontamination factors (DF's) corresponding to the current 10 nCi/gm criterion as a function of Θ , for the two contamination levels. These values for 1.4 and 10.4 years are in reasonable agreement with DF's estimated by Dillon et al⁽¹²⁾ for similar clad waste. The data of Table 9 are plotted versus Θ in Figure 5.

Decontamination data for clad waste are very sparse. Blomeke and Perona⁽⁵⁾ reported that repeated leaching of a Zircaloy plus stainless steel clad waste from highly irradiated fuel in a 8-10M HNO_3 solution, followed by water rinsing

TABLE 7. Aggregate Radioactivity According to Nuclide Class
For HLW and Clad Waste

<u>CLAD WASTE (DC Model)^(a)</u>						
<u>$\Theta(\text{yr})$</u>	<u>TRU's (Ci/MTU)</u>	<u>FP</u>	<u>LM</u>	<u>$\Sigma(\text{Ci/MTU})$</u>	<u>$\Sigma(\text{MCi/MTU})$</u>	<u>$\Sigma\text{MCi/GWe-yr}$</u>
1.4	6.10+1	8.40+2	7.78+3	8.68+3	8.68-3	2.95-1
10.4	4.35+1	1.56+2	2.39+3	2.59+3	2.59-3	8.81-2
100	6.95	1.71+1	2.68+2	2.92+2	2.92-4	9.94-2
1000	1.11	1.05-2	4.24	5.36	5.36-6	1.82-4
10000	7.60-1	9.95-3	3.95	4.72	4.72-6	1.61-4
100000	7.45-2	7.65-3	3.95	4.03	4.03-6	1.37-4
<u>HLW^(b)</u>						
1.4	7.28+3	1.68+6		1.69+6	1.69	5.75+1
10.4	2.35+3	3.12+5		3.14+5	3.14-1	1.07+1
100	3.10+2	3.42+4		3.45+4	3.45-2	1.17
1000	7.82+1	2.09+1		9.91+1	9.91-5	3.37-3
10000	2.28+1	1.99+1		4.27+1	4.27-5	1.45-3
100000	2.73	1.53+1		1.80+1	1.80-5	6.13-4

- a. Diablo Canyon fuel model (see Table 4)
LWR(U) reactor, 33 GWD/MT burnup; 34.03 MTU/GWe-yr
0.05 w/o spent fuel U and TRU's in clad waste (data from Ref. 3,6)
100 w/o light metal (LM) in clad waste
0.05 w/o spent fuel fission products (FP) in clad waste
- b. 0.5 w/o spent fuel U and Pu in HLW (data from Ref. 3,6)
99.95 w/o of other TRU's in HLW
99.95 w/o fission products in HLW

FIGURE 3. Specific Radioactivity (GWe·yr Basis) Burden for HLW and Clad Waste Versus Post-Reactor Discharge Time

FIGURE 4. Comparison of Aggregate Radioactivity Densities for HLW and Clad Waste Versus Post-Reactor Discharge Time

TABLE 8. TRU's Burden (nCi/g) in Clad Waste for Several Contamination Levels

$\theta(\text{yr})$	$100\%(\text{SF})^{(a)}$ (MCi/MTU) TRU's	$100\%(\text{SF})^{(b)}$ (nCi/g) TRU's/CW	0.10 w/o (nCi/g) TRU's/CW	0.05 w/o (nCi/g) TRU's/CW
1.4	1.22-1	4.50+8	4.50+5	2.25+5
10.4	8.70-2	3.21+8	3.21+5	1.61+5
100	1.39-2	5.12+7	5.12+4	2.56+4
1000	2.19-3	8.08+6	8.08+3	4.04+3
10000	1.50-3	5.54+6	5.54+3	2.77+3
100000	1.13-4	4.17+5	4.58+3	2.29+3

- a. data from Ref. 6 (p.2.C.7), bringing Pu isotopes to spent fuel (SF) level
b. for DC fuel model, 1MCi/MTU per 271 kg CW/MTU = 3.69+9 nCi/g CW

TABLE 9. Decontamination Factors (DF) Corresponding to 10nCi/g Criterion for Several Contamination Values

$\theta(\text{yr})$	$\text{DF}_{10\text{nCi/g}}^{(a)}$	
	$0.1 \text{ w/o}^{(b)}$	0.05 w/o
1.4	4.5+4	2.3+4
10.4	3.2+4	1.6+4
100	5.1+3	2.6+3
1000	8.1+2	4.0+2
10000	5.5+2	2.8+2
100000	4.6+2	2.3+2

- a. $\text{DF} = \text{amount in}/\text{amount out} = \text{amount in (nCi/g)}/10 \text{ nCi/g}$
b. amount of contamination of clad waste by spent fuel TRU's

FIGURE 5. Clad Waste Decontamination Factor (DF) Corresponding to 10nCi/g Criterion Versus Post-Reactor Discharge Time

after each leaching, reduced the Pu activity to about 700 nCi/g, an observation which tends to highlight the severity of the 10 nCi/g restriction on burial of TRU's contaminated waste. Dillon et al⁽¹²⁾ report on BNWL decontamination work on Zircaloy, illustrating the physico-chemical complexity of the decontamination process.

As noted in the previous data compilations for the HLW and clad waste comparison, it is assumed that a certain fraction of the spent fuel U and Pu (namely 0.5 w/o for this comparison) is carried over in the HLW stream, and virtually all other nuclides from ²⁰⁷Tl to ²⁴⁷Cm as well.^(3,4,6) The clad waste is assumed to carry a certain fraction (namely, 0.05 w/o for this comparison) of the total spent fuel burden of nuclides from ²⁰⁷Tl to ²⁴⁷Cm. Considering the intimate conjunction of the cladding and the fuel, and the processes which generate the HLW, these appear to be reasonable assumptions, though not necessarily supportive of the numerical values of the contamination.

Using previously cited radioactivity data sources, and a spent fuel U and Pu recovery factor of 0.995, the TRU's activity fraction together with those of the uranium isotopes and the remaining isotopes from ²⁰⁷Tl to ²⁴⁷Cm are given in Table 10 as a function of Θ . These data show that the TRU's activity dominates the radioactivity burden of both the HLW and clad waste streams out to roughly 10,000 years. Under the above contamination and fractionation assumptions, TRU's activity fractions for the HLW and clad waste are virtually equal out to this time. The uranium isotope activity fraction becomes dominant for the clad waste between 10^5 and 10^6 years.

TABLE 10. Radioactivity Fractions for Various Nuclide Groups Within the Class ^{207}Tl to ^{247}Cm for HLW and Clad Waste

[LWR(U) Reactor, 33MWD/MT Burnup] [Diablo Canyon Fuel Model]						
$\theta(\text{yrs})$	HLW ^(a)			CW ^(b)		
	TRU's	U	Other	TRU's	U	Other
0.4	1.00	0	0	1.00	0	0
1.4	1.00	0	0	1.00	0	0
10.4	1.00	0	0	1.00	0	0
100	1.00	0	0	1.00	0	0
1000	0.995	0.005	0	0.987	0.005	0.008
10^4	0.978	0.003	0.019	0.993	0.002	0.005
10^5	0.343	0.062	0.595	0.763	0.228	0.009
10^6	0.085	0.093	0.822	0.004	0.949	0.047
10^7	0.077	0.111	0.812	0	0.962	0.038
10^8	0	0.143	0.857	0	0.971	0.029
10^9	0	0.139	0.861	0	0.969	0.031

- a. assuming contamination by 0.5 w/o U and Pu of spent fuel, plus 99.95 w/o of other isotopes from ^{207}Tl to ^{247}Cm (see Ref. 3,4,6)
- b. assuming contamination by 0.05 w/o of spent fuel isotopes from ^{207}Tl to ^{247}Cm

4.3 RADIOLOGICAL HAZARD COMPARISON

Using the radiological hazard index discussed previously, the indices for the various nuclide classes are given for the clad waste in Table 11, and for the HLW in Table 12. Data are presented on both MTU and GWe-yr bases. Data sources and calculation technique are the same as cited in Section 3.0. Both air and water values are given, noting that the lowest air/water MPC value for a given nuclide was used in the calculation. Radiological hazard index values (MTU basis) for air and water, for the various nuclide classes, are plotted versus Θ in Figure 6 for the clad waste. Figure 7 presents similar information for the HLW. It is apparent that these data exhibit fairly complex time profiles and that statements about the relative radiological importance of various nuclides in HLW and clad waste must be qualified by a corresponding time specification.

Using the MTU specific volume data for HLW and clad waste given in Table 5 for various forms of these wastes, the air hazard "densities" were computed for the TRU's and the fission products (FP's), for the indicated range of densification for the HLW and the clad waste. These data are plotted in Figure 8 versus Θ . For the assumed contamination (see footnotes in Tables 11 and 12) it is seen that, depending on the densification, the critical TRU's radiological "densities" for the HLW and the clad waste can be quite comparable over a broad range of Θ . Although there is substantially greater difference in the FP data, appreciation of the practical significance of this difference from a waste management standpoint would require more comprehensive analysis of the radiological (more generally, the biological) hazard aspect.

Under the contamination assumptions of this comparison, and on the basis of the radiological hazard index, it appears evident that the waste management problem for clad waste can be comparable in severity to that of the HLW over a Θ range which extends well into the ultimate disposal regime of waste management.

TABLE 1. Radiological Hazard Index for Clad Waste
According to Nuclide Class

[DC Fuel Model^(a)
LWR(U) Reactor
33 GWD/MT Burnup]

m³/MTU Basis^(b)

<u>θ(yr)</u>	<u>TRU's</u>		<u>FP's</u>		<u>LM's</u>		<u>ΣAir</u>	<u>ΣWater</u>
	<u>Air</u>	<u>Water</u>	<u>Air</u>	<u>Water</u>	<u>Air</u>	<u>Water</u>		
1.4	1.5+14	8.5+5	3.0+12	1.6+8	1.9+13	2.1+8	1.7+14	3.7+8
10.4	1.7+14	6.5+5	1.2+12	1.1+8	6.0+12	7.4+71	1.8+14	1.9+8
100	9.5+13	2.4+5	1.2+11	1.1+7	1.3+11	8.7+69	9.5+13	2.0+7
1000	1.8+13	4.2+4	4.1+6	4.0+1	3.6+8	2.8+41	1.8+13	7.0+4
10,000	1.3+13	2.6+4	4.0+6	4.0+1	2.2+8	1.9+41	1.3+13	4.5+4

m³/GWe.yr Basis^(c)

1.4	5.1+15	2.9+7	1.0+14	5.4+9	6.5+14	7.2+9	5.0+15	1.3+10
10.4	5.8+15	2.2+7	4.1+13	3.7+9	2.0+14	2.5+9	6.0+15	6.2+9
100	3.2+15	8.2+6	4.1+12	3.7+8	4.4+12	3.0+8	3.2+15	6.8+8
1000	6.1+14	1.4+6	1.4+8	1.4+3	1.2+10	9.5+5	6.1+14	2.4+6
10,000	4.4+14	8.8+5	1.4+8	1.4+3	7.5+9	6.5+5	4.4+14	1.5+6

a. 0.05 w/o spent fuel TRU's and U in clad waste

0.05 w/o spent fuel FP's in clad waste

100 w/o LM's in clad waste

b. m³ refers to volume (air/water) needed to bring given nuclide concentration to MPC limit as specified in Ref. 7

c. m³/GWe.yr = m³/MTU x 34.03 MTU/GWe.yr

TABLE 12. Radiological Hazard Index for HLW According to Nuclide Class

LWR(U) Reactor ^(a) 33 GWD/MT Burnup <u>m³/MTU Basis^(b)</u>						
<u>Θ(yr)</u>	<u>TRU's</u>		<u>FP's</u>		<u>ΣAir</u>	<u>ΣWater</u>
	<u>Air</u>	<u>Water</u>	<u>Air</u>	<u>Water</u>		
0.4	1.4+16	1.3+9	1.0+16	4.5+11	2.4+16	4.5+11
3.4	9.8+15	3.9+8	3.4+15	2.7+11	1.3+16	2.7+11
10.4	8.0+15	3.0+8	2.3+15	2.1+11	1.0+16	2.1+11
100	1.9+15	6.4+7	2.4+14	2.3+10	2.1+15	2.3+10
1000	4.4+14	1.6+7	8.4+9	8.3+4	4.4+14	1.6+7
10,000	1.6+14	3.7+6	8.0+9	8.0+4	1.6+14	3.8+6

<u>m³/GWe·yr Basis^(c)</u>						
0.4	4.8+17	4.4+10	3.4+17	1.5+13	8.2+17	1.5+13
3.4	3.3+17	1.3+10	1.2+17	9.2+12	4.5+17	9.2+12
10.4	2.7+17	1.0+10	7.8+16	7.2+12	3.5+17	7.2+12
100	6.5+16	2.2+9	8.2+15	7.8+11	7.3+16	7.8+11
1000	1.5+16	5.4+8	2.9+11	2.8+6	1.5+16	5.4+8
10,000	5.4+15	1.3+8	2.7+11	2.7+6	5.4+15	1.3+8

- a. 0.5 w/o of spent fuel Pu and U in HLW
99.95 w/o of other spent fuel TRU's in HLW
all tritium, noble gases removed from HLW
99.9 w/o halogen FP's removed from HLW
99.95 w/o of other FP's in HLW
- b. m³ refers to volume (air/water) needed to bring given nuclide concentration to MPC limit as specified in Ref. 7
- c. m³/GWe·yr = m³/MTU x 34.03 MTU/GWe·yr

FIGURE 6. Clad Waste Radiological Hazard Index (Air and Water)
Versus Post-Reactor Discharge Time

FIGURE 7. HLW Radiological Hazard Index (Air and Water)
Versus Post-Reactor Discharge Time

FIGURE 8. Comparison of Radiological Hazard Density (Air) for HLW and Clad Waste Versus Post-Reactor Discharge Time

4.4 THERMAL POWER COMPARISON

Aggregate thermal power data for the various nuclide classes are given in Table 13 for HLW and clad waste as a function of θ . Data citations are given in the table and contamination assumptions remain the same as for the previous comparisons. Total thermal power is given on both MTU and GWe·yr bases. The total thermal power (GWe·yr basis) is plotted versus θ in Figure 9 for the HLW and the clad waste. Using Table 5 data for the various MTU specific volumes for HLW and clad waste, thermal power "densities" were computed for the HLW and the clad waste. These are plotted in Figure 10 versus θ , for the range of densification given in Table 5. On both GWe·yr and m^3 bases (Figures 9 and 10, respectively) it is seen that the HLW presents a substantially greater thermal power problem than does the clad waste. Appreciation of the technico-economic significance of the indicated difference would, however, require an analysis similar to that performed by Blomeke and Perona⁽⁵⁾ for the interim storage, shipment, and ultimate disposal phases of clad waste management. In the latter study, a computer code was developed for storage and shipment container design, and geologic storage techniques, which is sensitive to both the thermal power and the radiological hazard of the waste.

TABLE 13. Aggregate Thermal Power According to Nuclide Class for HLW and Clad Waste

<u>Clad Waste (DC Model)^(a)</u>					
<u>θ(yr)</u>	<u>TRU's (MW/MTU)</u>	<u>FP^(c)</u>	<u>LM^(d)</u>	<u>ΣMW/MT</u>	<u>ΣMW/GWe·yr</u>
0.4	4.64-7	9.95-6	6.95-4	7.05-4	2.40-2
1.4	4.34-7	3.93-6	1.05-4	1.09-4	3.71-3
10.4	3.95-7	5.10-7	2.71-5	2.80-5	9.53-4
100	2.11-7	5.25-8	4.26-8	3.06-7	1.04-5
1000	3.34-8	1.13-11	4.74-11	3.35-8	1.14-6
10,000	2.30-8	1.04-11	-	2.30-8	7.83-7
100,000	2.27-9	6.70-12	-	2.28-9	7.76-8
<u>HLW^(e)</u>					
0.4	8.05-4	1.99-2		2.07-2	7.04-1
1.4	2.44-4	7.85-3		8.09-3	2.75-1
10.4	6.99-5	1.02-3		1.09-3	3.71-2
100	9.57-6	1.05-4		1.15-4	3.91-3
1000	2.10-6	2.25-8		2.12-6	7.21-5
10,000	5.20-7	2.08-8		5.41-7	1.84-5
100,000	6.48-8	1.34-8		7.82-8	2.66-6

- a. Diablo Canyon fuel model (see Table 4)
 LWR(U) reactor, 33 GWD/MT burnup, 34.03 MTU/GWe·yr
0.05 w/o spent fuel U and TRU's in clad waste
100 w/o light metals (LM) in clad waste
 0.05 w/o fuel fission products (FP's) in clad waste
- b. U and TRU's data from Ref. 6, bringing Pu and U isotopes to spent fuel level
- c. FP data from Ref. 6
- d. LM data from Ref. 4 (Table 3.29), using table data for short term values; long term data obtained from decay constants calculated from table data
- e. 0.5 w/o spent fuel U and Pu in HLW
 99.95 w/o of other TRU's in HLW
 99.95 w/o FP's in HLW

FIGURE 9. Specific Thermal Power (GWe·yr Basis) Burden for HLW and Clad Waste Versus Post-Reactor Discharge Time

FIGURE 10. Comparison of Aggregate Thermal Power Density for HLW and Clad Waste Versus Post-Reactor Discharge Time

5.0 COMPARISON OF RADIOACTIVITY AND THERMAL POWER OF CLAD WASTE FOR REFERENCE FUEL ASSEMBLY AND DIABLO CANYON FUEL MODELS

The HLW clad waste comparison of this report is primarily based on the LWR(U) reactor at 33 GWD/MT burnup, using the Diablo Canyon Reference Fuel Model. The Reference Fuel Assembly Model⁽⁹⁾ refers to a LWR using a mixed oxide fuel, incorporating first recycle Pu, at a burnup of 25 GWD/MT. It is of interest to gain some measure of the effect of these system differences on the radioactivity and thermal power burdens of the clad waste.

A comparison for the various nuclide classes is given in Table 14 for the RFA and DC fuel models. Absolute values are given for the RFA model, while the R values are the ratios of the DC model value to the RFA model value on both energy (GWe·yr) and volume (m³) bases. Average R values over the Θ range 1.4 - 10,000 years are also given as a rough measure of comparison for the various nuclide classes. Considering the average R values, as well as the spread in individual values for all nuclide classes, it is evident that the differences between the RFA and DC fuel models are not large and are, in fact, generally within variations which could be effected by reasonable changes in TRU's and fission product contamination assumptions, and clad waste composition assumptions. If this conclusion is valid, then data given in this review for the DC clad waste, for a LWR(U) and 33 GWD/MT system, has a fairly broad range of utility, spanning both uranium and Pu recycle fuels, burnups ranging from 25 to 33 GWD/MT, and clad waste compositions which include most reasonable assumptions in this respect. Furthermore, most technico-economic analyses incorporating the technical characteristics of clad waste given in this review will probably involve uncertainties in economic and public hazard factors which far outweigh the differences in clad waste characteristics noted above. It is suggested that a simple averaging of the technical characteristics of the RFA and the DC fuel models, as a function of Θ , would provide clad waste data satisfactory for the purposes of broad scoped economic and public hazard analysis. Considering the nuclear power projections in the WASH-1139 series,⁽²⁾ the utility of such data should extend well beyond the year 2000.

TABLE 13. Comparison of Radioactivity and Thermal Power Burdens of Clad Waste For RFA and DC Fuel Models

θ (yrs)	TRU's (a)						FP's (a)						LM's (a)					
	Ci/GWe·yr ^(b)	W/GWe·yr	R_e^{Ci}	R_V^{Ci}	R_e^W	R_V^W (c)	Ci	W	R_e^{Ci}	R_V^{Ci}	R_e^W	R_V^W	Ci	W	R_e^{Ci}	R_V^{Ci}	R_e^W	R_V^W
1.4	6.8+3	4.4+1	.31	.48	.34	.53	4.6+3	2.1+2	(6.3)	(9.8)	.62	.97	1.6+6	8.6+3	.16	.25	.42	.66
10.4	4.3+3	2.2+1	.35	.55	.59	.92	5.5+3	1.6+1	.96	1.5	1.1	1.7	1.8+5	1.3+3	.45	.70	.71	1.1
100	3.6+2		.67	1.1			5.9+2		.98	1.5			5.5+3		1.7	2.6		
1000	8.2+1		.46	.72			4.1-1		.88	1.4			1.2+2		1.1	1.7		
10,000	2.0+1		1.3	2.0			3.8-1		.68	1.1			8.2+1		1.6	2.5		
average 'R' values:			.62	.96	.47	.73			.88	1.4	.84	1.3			.99	1.5	.57	.89

a. First Pu recycle MOX fuel used for RFA; enriched U only for DC model; 25 GWD/MT and 33 GWD/MT burnups, respectively

0.05 w/o of spent fuel U and TRU's and FP's assumed to contaminate RFA and DC clad waste; 100% light metals (LM's)

see Table 5 for RFA and DC fuel models compositions

b. absolute values refer to RFA model; data from Ref. 9 for RFA model; data from Ref. 3,4,6 for DC model

c. $R = \text{DC value/RFA value}$; R_e is ratio on GWe·yr basis; R_V is ratio on m^3 (clad waste) basis, using die compacted densities for both RFA and DC clad waste (see Table 5); $R_V = R_e \times 1.56$, where 1.56 is ratio of $(\text{GWe}\cdot\text{yr}/\text{MTHM}) \times (\text{MTHM}/\text{m}^3)$ product for DC and RFA models, using 32.5 and 32% overall efficiency, respectively

6.0 SOME TECHNICAL MEASURES OF THE WASTE MANAGEMENT PROBLEM OF CLAD WASTE RELATIVE TO HIGH LEVEL WASTE

Until comprehensive optimization analysis reveals a better measure of the economic/public hazard significance of the various technical indices discussed in this brief review, the simple ratio of these indices for the HLW and clad waste provides a reasonably good and unambiguous measure of the relative importance of these waste streams. Table 15 summarizes these data for the volume, radioactivity, radiological hazard and thermal power indices previously discussed, as a function of θ . The upper part of the table gives these ratios on the basis of the GWe·yr. The lower part gives the comparison on a unit volume (m^3) basis, for both uncompacted and compacted waste (see table for identification of these waste forms).

The volume comparison is relatively clear and that for the compacted forms is well within current technical competence. Under the compaction assumptions used here, the waste management problem from a volume/GWe·yr standpoint is virtually identical for the HLW and the clad waste. The practical interpretation of the other ratios is much less clear. Under the contamination assumptions used in this comparison, it is evident that the HLW presents more severe radiological and thermal power problems than the clad waste over the entire range of θ . Optimization analysis of the nuclear waste management problem is in progress in this country and abroad. (e.g., 4,5,13) Obviously, simple ratios such as the above will find little use in such analysis, although the discovery of simple (possibly dimensionless) property groups for the various nuclear waste streams, which can be incorporated in comprehensive economic/public hazard optimization analysis, would be useful indeed. The statement that HLW is "worse than clad waste" from a waste management standpoint is well supported. The quantification of this statement in economic/public hazard terms appears, however, to pose very substantial analytical problems at this time.

TABLE 15. Some Technical Measures of Waste Management Problem
Of Clad Waste Relative to HLW

[Diablo Canyon Fuel Model]
LWR(U) Reactor
33 GWD/MT Burnup

GWe·yr Basis (ratio CW value to HLW value)

$\Theta(\text{yr})$	Volume ^(a)		RA ^(b)	Rad. Hazard ^(c)		Thermal Power ^(d)
	unc.	comp.		air	water	
1.4	6.0-1	1.0	5.1-3	8.9-3	1.0-3	1.4-2
10.4	6.0-1	1.0	8.2-3	1.7-2	8.6-4	2.6-2
100	6.0-1	1.0	8.5-2	4.4-2	8.7-4	2.7-3
1000	6.0-1	1.0	5.4-2	4.1-2	4.4-3	1.6-2
10,000	6.0-1	1.0	1.1-1	8.2-2	1.2-2	4.3-2
100,000	6.0-1	1.0	2.2-1			2.9-2

Unit Vol. Basis (ratio CW value/ m^3 to HLW value/ m^3)^(e)

$\Theta(\text{yr})$	RA		Radiological Hazard				Thermal Power	
			air		water			
	unc.	comp.	unc.	comp.	unc.	comp.	unc.	comp.
1.4	8.5-3	5.1-3	1.5-2	8.9-3	1.7-3	1.0-3	2.3-2	1.4-2
10.4	1.4-2	8.2-3	2.8-2	1.7-2	1.4-3	8.6-4	4.3-2	2.6-2
100	1.4-1	8.5-2	7.3-2	4.4-2	1.5-3	8.7-4	4.5-3	2.7-3
1000	9.0-2	5.4-2	6.9-2	4.1-2	7.3-3	4.4-3	2.7-2	1.6-2
10,000	1.8-1	1.1-1	1.4-1	8.2-2	2.0-2	1.2-2	7.2-2	4.3-2
100,000	3.7-1	2.2-1					4.8-2	2.9-2

- a. uncompacted refers to uncompacted clad waste ($0.23 \text{ m}^3/\text{MTU}$) and liquid concentrate HLW ($0.38 \text{ m}^3/\text{MTU}$); compacted refers to die compacted clad waste ($0.06 \text{ m}^3/\text{MTU}$) and vitrified HLW ($0.06 \text{ m}^3/\text{MTU}$). See Table 5
- b. RA refers to aggregate radioactivity (see Table 7)
- c. see Tables 11 and 12 for data and assumptions
- d. see Table 13 for data and assumptions
- e. unit volume basis = $\text{GWe}\cdot\text{yr basis} \times [(\text{m}^3/\text{GWe}\cdot\text{yr})_{\text{HLW}}/(\text{m}^3/\text{GWe}\cdot\text{yr})_{\text{CW}}]$
 = $\text{GWe}\cdot\text{yr basis} \times 1.67$ for uncompacted waste
 = $\text{GWe}\cdot\text{yr basis} \times 1.00$ for compacted waste

7.0 CONCLUSION

This brief review has attempted some relative characterization of the HLW and clad waste streams for a nuclear power segment dominated by LWR's. Although the comparison has focused primarily on the LWR(U) reactor at 33 GWD/MT burnup and a specific fuel model (Diablo Canyon Reference Model), some data are presented which suggest that the clad waste technical characteristics displayed here may have considerably more general utility in optimization analysis of nuclear waste management up to roughly the year 2000.

The extent to which various actions on clad waste [e.g., decontamination, densification, useful (radioactive) product manufacture] will perturb the overall economic/public hazard situation for nuclear waste management has received some attention^(e.g., 4,5,8) and the relative importance of the clad waste indicated by this review tends to support considerably more work in this regard. The similarity in some of the technical characteristics of the HLW and the clad waste streams suggests the question of whether, or not, some combination of these streams would be expedient and practicable from an overall waste management standpoint. Apart from the transmutation concept,⁽⁶⁾ at a given post-reactor discharge time the nuclear spent fuel presents a virtually constant array of potentially harmful species for control over geologic time spans. The optimization of the physico-chemical forms for this array, and of the interfaces between these forms and the biosphere, is the essential problem of which the high level waste and the clad waste are principal parts under reasonable contamination assumptions.

This optimization has a number of constraints. Attentive to the paramount public hazard factor, a code of Federal regulations will continue to evolve that will effect a variable influence on waste management strategy. The 10 nCi/g limit on burial of TRU's contaminated material, and the 10 year limit on the generation-liquid storage-solidification-solid storage-shipment to Federal depository segment of HLW management, are examples. The array of factors common to technico-economic analysis is involved, many of which can only be virtually crude guesses over a long time span. The character and extent of the nuclear power commitment over some multiple of the minimum

technico-economic planning period are involved. The evolution of technology in treating, transporting and disposing of waste is involved. Probably most important, and most difficult to quantify, is the multitude of factors which determines the general acceptance of nuclear waste management by the public sector.

The prospects for substantial latitude in accomodating to public appraisal of waste management strategies are encouraging. There has been considerable analysis which indicates that the overall cost of nuclear power is not strongly perturbed by a broad scope of measures to minimize the long term public hazard associated with nuclear fuel cycle operations, including reprocessing and waste management. (e.g., 4,6,14)

8.0 REFERENCES

1. R. A. Wolfe, "Problems and Prospects in the Management of Solid Radioactive Waste", J. Environ. Sci., July-August 1975, p. 9.
2. Nuclear Power Growth 1974-2000, WASH-1139(74), February 1974.
3. J. O. Blomeke, C. W. Kee, J. P. Nichols, "Projections of Radioactive Waste to be Generated by the U.S. Nuclear Power Industry", ORNL-TM-3965, February 1974.
4. Siting of Fuel Reprocessing Plants and Waste Management Facilities, ORNL-4451, July 1970.
5. J. O. Blomeke, J. J. Perona, "Storage, Shipment and Disposal of Spent Fuel Cladding", ORNL-TM-3650, January 1972.
6. High Level Radioactive Waste Management Alternatives, BNWL-1900, Vol. 1, May 1974.
7. Code of Federal Regulations, Title 10, Chapter 1, Part 20, Appendix B, Table II, January 1975.
8. N. M. Levitz, B. J. Kullen, M. L. Steindler, "Management of Waste Cladding Hulls. Part 1. Pyrophoricity and Compaction", ANL-8139, February 1975.
9. Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle, ERDA-76-43, Vol. 1, Chapter 2, May 1976.
10. Ibid, Vol. 2, Chapter 6.
11. Ibid, Vol. 1, Chapter 3.
12. R. L. Dillon, B. Griggs, R. S. Kemper, R. G. Nelson, "Chemical Decontamination and Melt Densification of Chop-Leach Fuel Hulls", BNWL-SA-5696, March 22, 1976.
13. H. W. M. Braun, K. Ditterich, J. Schneider, "An Approach to the Optimal Management of Radioactive Wastes in the European Community by Means of Systems Analysis", Proc. Jahrestagung des Fachverbandes fur Strahlenschutz, Helgoland, September 1974.
14. B. C. Finney, R. E. Blanco, R. C. Dahlman, F. G. Kitts, J. P. Witherspoon, "Correlations of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing 'As Low as Practicable' Guides--Nuclear Fuel Reprocessing", ORNL-TM-4901, May 1975.

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