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September 1986

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

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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WASTE MANAGEMENT SYSTEM ALTERNATIVES FOR TREATMENT OF WASTES FROM SPENT FUEL REPROCESSING

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1.0 INTRODUCTION

A wide range of waste management system alternatives and combinations are available for management of the radioactive wastes that are produced during spent-fuel reprocessing. This report presents the results of a comparative evaluation of a selected set of these alternatives. Most concerns for reprocessing wastes have usually focused on the high-level waste (HLW); however, from a cost and performance standpoint, transuranic (TRU) wastes can have a comparable impact on the waste management system. Six different combinations of TRU waste treatment alternatives were selected for evaluation in this study. To identify the total impact of these alternatives on costs and waste form performance, however, the total waste management system must be considered because improved costs and/or performance in one area may result in lower performance or higher costs in another area. The waste management system considered in this evaluation includes waste processing at a fuel reprocessing plant (FRP), transportation of the wastes generated at the FRP to disposal facilities, and disposal of the wastes at a repository for HLW and TRU wastes and a near-surface burial facility for low-level wastes (LLW).

The objective of this study, which was performed for the U.S. Department of Energy (DOE) by Pacific Northwest Laboratory (PNL) operated for the DOE by Battelle Memorial Institute, was to help define a preferred TRU waste treatment alternative based on minimum waste management system costs, minimum system risks, and improved waste form performance in a geologic repository. These results, in turn, were to be used to assist in the development of TRU waste acceptance requirements that may be needed to meet regulatory requirements for disposal. The principal performance and cost impact issues addressed here include:

1. TRU waste volume reduction incentives
2. the impact of excluding untreated combustible TRU wastes from the repository
3. incentives for decontaminating spent fuel cladding hulls to LLW
4. incentives for incorporating TRU waste into HLW glass.

This is not intended to be an all-inclusive list of issues. It represents an initial selection of important cost and potential regulatory issues. This report represents a preliminary evaluation of these issues.

Most of the work reported here was completed in FY-1983 and FY-1984. The study was interrupted in mid-1984 to focus staff efforts on once-through fuel-cycle (non-reprocessing) waste disposal requirements. Spent-fuel reprocessing in this country had become a remote prospect and concerns are currently focused on wastes generated without fuel reprocessing. Work on this study was continued at a low priority level to complete the documentation of work already essentially completed. As a consequence, the analyses relating to cost and performance assessment comparisons are less comprehensive than originally planned.

2.0 SUMMARY AND CONCLUSIONS

This study was performed to help identify a preferred TRU waste treatment alternative for reprocessing wastes with respect to waste form performance in a geologic repository, near-term waste management system risks, and minimum waste management system costs. The results were intended for use in developing TRU waste acceptance requirements that may be needed to meet regulatory requirements for disposal of TRU wastes in a geologic repository. The waste management system components included in this analysis are waste treatment and packaging, transportation, and disposal. The major features of the TRU waste treatment alternatives examined here include.

1. packaging (as-produced) without treatment (PWOT)
2. compaction of hulls and other compactable wastes
3. incineration of combustibles with cementation of the ash plus compaction of hulls and filters
4. melting of hulls and failed equipment plus incineration of combustibles with vitrification of the ash along with the HLW

5a. decontamination of hulls and failed equipment to produce LLW plus incineration and incorporation of ash and other inert wastes into HLW glass

5b. variation of this fifth treatment alternative in which the incineration ash is incorporated into a separate TRU waste glass.

The six alternative processing system concepts provide progressively increasing levels of TRU waste consolidation and TRU waste form integrity. Vitrification of HLW and intermediate-level liquid wastes (ILLW) was assumed in all cases. Table 2.1 summarizes the six TRU waste treatment alternatives that were analyzed.

The analyses developed here are intended to define the relative advantages of these different treatment systems as opposed to a rigorous determination of total system costs and waste form performance. The analysis is based on a simplified scenario for the operation of the waste management system to identify

TABLE 2.1. Reprocessing Waste Treatment Alternative Descriptions

Waste Treatment	Hulls and	General Process Trash (GPT)		HEPA Filters		Failed	Fluorinator	SAC[(a)]
Alternative No.	Hardware	Noncombustible	Combustible	Frame	Media	Equipment	Solids	Waste
1	PWOT[(b)]	PWOT	PWOT	PWOT	PWOT	PWOT	PWOT	PWOT
2	Compact	Compact	Compact	Compact	Compact	PWOT	PWOT	Compact
3	Compact	Compact	Burn and Cement	Burn and Cement	Burn and Cement	PWOT	Cement	Burn and Cement
4	Melt	Melt	Burn and Vitrify w/HLW	As GPT[(c)]	Burn and Vitrify w/HLW	Melt	Cement	Burn and Vitrify/ Melt
5a	Decon	Decon Most, Cement Other	Burn and Vitrify w/HLW	Burn and Cement	Burn and Vitrify w/HLW	Decon Most, Cement Other	Cement	Burn and Vitrify/ Cement
5b	Decon	Decon Most, Melt Other	Burn and Vitrify w/ Other TRU	Burn and Vitrify/ Melt	Burn and Vitrify w/Other TRU	Decon Most, Melt Other	Vitrify w/ Other TRU	Burn and Vitrify/ Melt

---

(a) SAC = Sample and Analytical Cell.
(b) PWOT = Package without treatment.
(c) GPT = General Process Trash.

the specific effects of treatment, transport, and disposal alternatives. The basic assumptions that define the scenario are.

- Waste treatment facilities are associated with a 1,500 MTU/yr reprocessing plant and are operated at capacity.
- Repository capacity is 70,000 MTU-equivalent of reprocessing wastes.
- Repository receiving rates are 1,800 MTU/yr for the first five years, 3000 MTU/yr for the next twenty years, and 1,000 MTU in the 26th year.
- Total system costs are based on a 70,000 MTU-equivalent system or one filled repository. These estimates show that the predominant amounts of radionuclides in TRUW are expected to be in the cladding hulls and in the HEPA filters.
- Waste characteristics and quantities are based on the wastes that would have been generated at the Barnwell Nuclear Fuels Plant (BNFP) had it operated (Darr 1983).
- The SCOPE computer code was used to model the releases of radionuclides from TRU waste forms under representative salt, basalt, tuff, and granite ground water conditions.
- The relative benefits of treating the wastes are measured in terms of draft Environmental Protection Agency (EPA) regulations (40 CFR 191).
- Waste processing risks are based on average radiation exposure rates, estimated crew sizes, durations of the various operations, and the number of operations per year.
- Waste transportation risks were calculated using the "unit-risk factor" approach; separate unit risk factors (person-rem/km of travel) were used for each waste type and for both truck and rail transport modes.

Based on these assumptions, the following results were obtained.

The results of the long-term waste form performance assessment indicated that Alternative 4, hulls melting, was the most favorable alternative because the radionuclide dissolution rate is limited by the dissolution rate of the metal matrix. As a result, melted metal waste forms are clearly favored over other alternatives for metallic wastes. With compacted metallic waste forms, performance could be expected to increase as the compaction factor increases, especially if compactions appraching theoretical density can be obtained. Alternatives 1 to 3 (packaging without treatment, compaction, compaction plus incineration/cementation) were determined to produce the least favorable waste forms in terms of repository performance; however, this preliminary analysis is not adequate to distinguish between the performance of untreated combustible materials and cemented incinerator ash.

The near-term performance assessment provided mixed results. First, due to increasing complexity of the waste processing concepts, occupational routine and accident risks appear to favor Alternative 1, the minimum treatment alternative. These risks were also determined to increase progressively as the waste treatment facilities increase in complexity; i.e., the waste processing facility routine and accident risks increase in order from Alternative 1 to Alternative 5b. Transportation risks, which are largely determined by the volumes of material to be transported (which determines the number of shipments required), clearly favored Alternative 4 because it produces the lowest total waste volume. Also, Alternative 2 (compaction) has lower transportation risks than Alternative 1. These two observations indicate there is a significant incentive for reducing the volume of hulls and hardware to the maximum extent. However, decontaminating the hulls and hardware to produce low-level waste (LLW) as in Alternatives 5a and 5b has higher transport risks than Alterative 4, primarily because of a large LLW transport risk component.

Total life-cycle waste management system costs are presented in Table 2.2. Results indicate that increased waste treatment costs in the more complex alternatives were offset by reductions in transportation and disposal costs. Alternative 4 (metal melting plus incineration/vitrification) has the lowest system cost. Thus, a substantial incentive is shown for reducing the volume of hulls and hardware to the maximum possible extent. A significant cost reduction (about $2 billion) is also shown for Alternative 2 versus Alternative 1, which reinforces the previous statement regarding hulls and hardware volume reduction. No cost savings are shown for incineration of combustible wastes (Alternative 3) versus simple compaction (Alternative 2). Thus, from a system cost standpoint,

TABLE 2.2. Total Waste Management System Costs For Each Alternative

	Waste Treatment Alternative Costs ($ billions)					
	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incinceration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
Treatment Cost	1.24	1.42	1.70	1.72	1.83	1.83
Transport Cost	1.33	0.48	0.43	0.26	0.58	0.55
Disposal Cost						
HLW and TRUW	5.75	4.56	4.52	3.93	3.54	3.94
LLW	0.22	0.13	0.11	0.07	0.79	0.79
Total (rounded)	8.5	6.6	6.8	6.0	6.7	7.1

(a) All costs are given in billions of mid-1984 dollars

(b) Repository disposal costs are calculated for a bedded salt repository assuming co-emplacement and long-lived overpacks for all wastes no incentive is shown for incineration and subsequent cementation of combustible TRU waste. The decontamination alternatives show no cost incentive over the less complex compaction alternative but are still 20 to 30 percent lower in cost than the minimum treatment alternative.

The final step in the evaluation of waste treatment alternatives was to provide an approximate ranking of the alternatives based on the results of the performance assessments and cost analyses. This ranking was done by first listing each alternative in order of most preferred (assigned a value of 1) to least preferred, including ties, with respect to each of five evaluation parameters (life-cycle system costs, long-term waste form performance in the repository, near-term waste processing routine risks and accident risks, and transportation risks). The overall order in which these alternatives were ranked was then determined by counting the number of times each alternative was ranked least-preferred with respect to each evaluation parameter. The least-preferred alternative was assumed to be the alternative that was ranked least-preferred in the most evaluation categories. Ties were broken by adding together and comparing the sum of the ranking values for the otherwise equivalent alternatives.

The approximate ranking of waste treatment alternatives is summarized in Table 2.3. As shown, Alternative 4 was ranked as the most preferred alternative. This was primarily because of a large reduction in TRU waste volumes and an improvement in long-term waste form performance that results from hulls melting. Alternative 2 (compaction) was ranked higher than Alternative 1 (PWOT) but lower than Alternative 4 for similar reasons. This indicates a substantial incentive for reducing hulls and hardware waste volumes as much as possible. Although compaction reduces the hulls and hardware waste volumes, it does not improve waste form integrity to any appreciable extent. Alternative 3, which improves waste form integrity by incinerating and subsequent cementing of combustible wastes, did not show a significant improvement in long-term repository performance over Alternative 2 and was, therefore, ranked lower. However, the results of the long-term performance assessment are preliminary. Further analyses are necessary to distinguish differences in waste form

TABLE 2.3. Approximate Ranking of TRU Waste Treatment Alternatives

Evaluation Parameter	Waste Treatment Alternative 1 PWOT	 2 Compaction	 3 Compaction + Incineration/ Cementation	 4 Metals Melting + Incinceration/ Vitrification	 5a Metals Decontamination + Incineration/ Vitrification to HLW	 5b Metals Decontamination + Incineration/ Vitrification as TRUW
Long-term performance of waste forms in repository	4	4	4	1	2	2
Near-term performance						
- Routine proces- risks	1	2	3	4	5	5
- Risks from processing accidents	1	2	3	4	5	5
- Transportation risks	6	4	3	1	5	2
Life-cycle costs	6	2	4	1	3	5
Number of least-preferrable scores	3	1	1	0	2	2
Approximate overall ranking	6	2	3	1	4	4

(a) Rankings are based on a maximum range of 1 to 6, including ties, with respect to each evaluation parameter. Ties were broken by adding together the ranking values and comparing the totals.

performance between these two alternatives. The decontamination alternatives (5a and 5b) were not ranked high because they were the least-preferred alternatives with respect to waste processing routine risks and accident risks. These two alternatives were ranked evenly because the increased costs that result from producing, transporting, and disposing of a separate TRU waste glass waste stream are offset by reductions in transportation risks.

3.0 DESCRIPTION OF WASTES TO BE TREATED

The quantities and radionuclide contents of the solid reprocessing wastes used in this report are primarily as estimated by Allied-General Nuclear Services (AGNS) personnel for operation of the BNFP (Darr 1983). Modifications to these estimates that were made by the authors of this report are discussed later in this section.

3.1 ORIGIN OF WASTE TYPES AT THE REFERENCE FUEL REPROCESSING PLANT

The hulls and hardware are the metallic (i.e., Zircaloy, Inconel, and stainless steel) portions of the spent-fuel elements. These portions remain after the elements are sheared and the uranium dioxide (UO_2) fuel fraction is removed by dissolving with nitric acid during reprocessing. The hulls and hardware are not only the most voluminous and heaviest waste type, they are also the most highly radioactive.

The GPT waste contains both combustible (e.g., paper, cloth, plastics, rubber) and noncombustible (e.g., metal, glass, cement) materials. The sample and analytical cell (SAC) waste is similar to the GPT waste.

Used HEPA filters comprise a large volume waste stream that presents some challenging treatment problems. The filters have either wooden or metallic frames and noncombustible (e.g., glass, asbestos) or combustible (e.g., paper) filter media. They also contain an appreciable amount of organic materials in the form of adhesives and rubber gaskets. Some filters also contain separators made of aluminum; however, in this study we are assuming that such filters would not be used in a reprocessing plant. The presence of aluminum could have adverse effects on some of the treatment options being examined.

Failed equipment comprises another metallic (primarily stainless steel) waste stream. Darr's (1983) estimates indicate that this is a low volume waste stream. The BNFP staff planned to store large pieces of failed equipment onsite until the plant was decommissioned, at which time the failed equipment would be treated along with (and considered as) decommissioning waste.

Fluorinator solids result from fluorination of the uranium product of the reprocessing plant. This waste stream is composed primarily of alumina (Al_2O_3) and calcium fluoride (CaF_2) particulates.

Except for the hulls and hardware, portions of all of these waste types are expected to exist as LLW as well as TRUW.

3.2 BASES FOR WASTE DESCRIPTIONS

For this study of various waste treatment alternatives, it was necessary to determine the relative amounts of combustible and noncombustible materials in the reprocessing wastes. A clear distinction of these two types was difficult to obtain from the Darr (1983) study of GPT and SAC wastes. Most of the difficulty came from the distinctions made by the BNFP staff between the fraction of the waste containers in which at least a portion of the waste is combustible, and the fraction of the contained waste which is combustible. Unless the waste is segregated, these fractions are not necessarily the same. The information listed in Appendix C of the Darr (1983) study does not provide all of the information needed to evaluate alternative waste treatment options.

The following bases for the GPT and SAC wastes which were adopted for this study, are based on values from the Darr (1983) study and knowledge of waste compositions and handling practices held by the authors of this report.

- The GPT waste from the Fuel Receiving and Storage Station (FRSS) is 95 vol% combustible and 5 vol% noncombustible and is not segregated into its combustible and noncombustible fractions.
- The GPT wastes from other portions of the reprocessing plant are segregated at the point of origin, with the result that the fraction of the combustible waste is equal to the fraction of the GPT containers that contain combustible wastes. All of these GPT wastes are 80 vol% combustible and 20 vol% noncombustible materials. Only for the GPT from the Plutonium Product Facility do these bases give quantities different from those given in the Oarr (1983) study.
- The SAC wastes are not segregated at the point of origin, so all of the containers contain both combustible and noncombustible wastes, as

indicated in Appendix C of the Darr (1983) study. Each SAC waste container holds a mixture of 60 vol% combustible and 40 vol% noncombustible waste; these somewhat arbitrary fractions are based on PNL's interpretation of information for SAC waste stream 23 described in Appendix B of the Darr (1983) study. These bases give different quantities than those in Darr's Appendix C for both of the SAC waste streams.

- The weight percentages of the combustible and noncombustible portions of the GPT and SAC streams are the same as the volume percentages. This basis is admittedly arbitrary but is believed to be reasonable since Darr (1983) applied the same weight per drum to all of the drums of GPT waste, even though he appears to have assumed that segregation had occurred.

Another important consideration not evident in the BNFP staff estimates is that all HEPA filters, even those with metal frames, contain an appreciable amount of organic material such as adhesives. All of this waste stream must therefore be considered partially combustible, even though Darr (1983) applied that designation only to the wood-framed filters. PNL estimated that a typical HEPA filter is 33 wt% filter frame, 33 wt% filter media, and 33 wt% adhesives.

These bases/assumptions have no effect on the Darr (1983) estimates of initial waste volumes and numbers of containers. However, they are important for the considerations of alternative waste treatment processes in this study.

3.3 QUANTITIES OF WASTES

The quantities of different reprocessing wastes that fall into various waste categories are summarized here in a series of tables. More detailed data are contained in Section A.1 of Appendix A. The wastes are categorized as LLW, with three different subdivisions that are based on the radionuclide content, and as TRUW, with four different dose rate ranges. While this study emphasizes TRUW treatment alternatives, LLW is also included because of the possible impacts of these wastes on the TRUW treatment economics (e.g., treatment in the same facilities). The low-level wastes are divided among Classes A, B, and C (as defined in 10 CFR 61). Only the LLW Class A (LLW-A) wastes can be sent to shallow-land burial in regular drums without treatment. Low-level waste Classes B and C (LLW-B and LLW-C) must be treated to put them in waste forms or containers designed to be stable for 300 years before they can be placed in shallow-land burial.

The TRU wastes are divided into contact-handled (CH) and remotely-handled (RH) categories. Contact-handled waste is defined as wastes contained within drums and having a radiation dose rate below 200 mR/hr at the surface of the containers. The remotely handled TRU wastes are also characterized in several dose rate ranges.

The containers planned for the BNFP wastes as they were generated were 50-, 80-, and 600-gal drums. The standard 55-gal drum was planned to be used extensively. Because standard HEPA filters do not fit into 55-gal drums, 80-gal drums (military specification 27683) were to be used to contain most of these wastes. Specially designed 600-gal stainless steel containers equipped for remote handling were to be used to contain the hulls and hardware, the larger pieces of failed equipment, the SAC wastes, and the most highly radioactive HEPA filters.

Table 3.1 contains a summary of the Darr (1983) estimates of the numbers of initial waste containers produced each year to reprocess spent fuel at a rate of 1500 MTU/yr. The initial containers are those in which the wastes are collected and moved from the part of the facility where they were generated. The results are tabulated by container size and type of waste and are allocated among several dose rate ranges. These values are based on the data published by Darr (1983, Appendix C), without including the container weight in defining the TRU level. (Note that if the weight of the container had been included, there would have been some decrease in the quantity of TRUW and a corresponding increase in the quantity of LLW-C. The overall effect of this change, however, would be small.)

The wastes from the iodine retention operations are excluded from Table 3.1 and from subsequent consideration, because of the special disposal requirements for such wastes and because of their small volume. Treatment of

TABLE 3.1. Initial Containers Per Year in Low-Level and TRU Waste Classes

		Drum/yr in Indicated Low-Level Waste Class			Drum/yr of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
Container Size and Waste Type	Stream Number[a]	A	B	C	<200	200-10^3	10^3-10^4	>10^4	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	625	--	--	--	--	--	--	625	--	--	625
- Segregated Combustible	27,28,29,47,48,53,65,66	6912	--	974	432	84	74.4	--	7,886	432	158.4	8,476
- Segregated Noncombustible	27,28,29,47,48,53,65,66	1728	--	243	108	21	18.6	--	1,971	108	39.6	2,119
- Total GPT									10,482	540	198	11,220
Failed Equipment	11A,51A	8	17	--	70	--	--	--	25	70	--	95
Particulate Solids	41,42,43	4035	--	327	--	93	--	--	4,362	--	93	4,455
Metal-Framed Filters	26B,52B	10	--	--	50	--	--	--	10	50	--	60
Total in 55-Gal Drums									14,879	660	291	15,830
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	15	20	25.5	153	52	12	--	60.5	153	64	277.5
Metal-Framed Filters	25B,26A,26C,45,46,52A,63B, 63C,64	71	9	28.5	961	56	13	--	108.5	961	69	1,138.5
Total in 80-Gal Drums									169	1,114	133	1,416
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	300	--	--	300	300
Failed Equipment	11B,24,44,51B,62	19	6	13	4	1	2	1	38	4	4	46
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	44	--	--	44	44
Sample and Analytical Cell (SAC) Waste	23,67	--	--	4	--	28	6	3	4	--	37	41
Total in 600-Gal Drums									42	4	385	431
Total All Drums									15,090	1,778	809	17,677

(a) Data and stream numbers are taken from Darr (1983) for reprocessing 1500 MTU/yr.

Note: (1) Container weights not included in defining TRU level.
(2) Wastes from iodine retention operations not included (78 55-gal drum/yr).
(3) Values may be converted to container/MTU by dividing by 1500.

such wastes can be considered separately. Costs of such treatment would certainly be only a small fraction of the costs of treating the wastes addressed in this study.

Table 3.2 contains a summary of the volumes occupied by the initial containers, again using values provided by Darr (1983). In this and subsequent tables the quantities are given per MTU processed. The volumes in this table represent the volumes of waste to be disposed of if disposal in the initial containers is possible.

The volumes of untreated wastes before they are placed in the initial containers are given in Table 3.3. These values represent the starting volumes for waste treatment processes and are occasionally much smaller than the volumes of the initial containers because of inefficient packing. This is especially important with filters that are packaged individually in drums. These volumes of untreated wastes were obtained by calculating the volumes of untreated wastes per container from the data published by Darr (1983, Appendix B) and multiplying those values by the number of containers filled per MTU processed.

Table 3.4 contains the weight of the various wastes. These data also come directly from the Darr (1983) study.

Table 3.5 presents a summary comparison of the volumes of the initial waste drums containing the different types of waste that will require treatment and/or repository disposal (the LLW-B, LLW-C and the TRUW). Because of their initially high volumes, potential cost savings attainable by volume reduction processes are obviously the greatest for the hulls and hardware, the filters, and the GPT. Treatment facilities for the hulls and hardware and the filters can be sized without consideration of low-level waste treatment requirements. However, the quantities of LLW requiring treatment are greater than the quantities of TRUW for the GPT, the failed equipment, and the particulate solids. Thus, treatment of both the LLW and TRUW components of these wastes in the same facility may be indicated.

The potential impact of a plus-or-minus threefold uncertainty in Darr's (1983) radionuclide content estimates on the TRUW quantities is addressed in

TABLE 3.2. Volume of Initial Containers Containing the Untreated Wastes

Container Size and Waste Type	Stream Number[a]	m^3/MTU in Indicated Low-Level Waste Class			m^3/MTU of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
		A	B	C	<200	$200-10^3$	10^3-10^4	$>10^4$	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	0.108	--	--	--	--	--	--	0.108	--	--	0.108
- Segregated Combustible	27,28,29,47,48,53,65,66	1.189	--	0.168	0.074	0.014	0.013	--	1.356	0.074	0.027	1.458
- Segregated Noncombustible	27,28,29,47,48,53,65,66	0.297	--	0.042	0.019	0.0036	0.0032	--	0.339	0.019	0.0068	0.364
- Total GPT									1.803	0.093	0.034	1.930
Failed Equipment	11A,51A	0.0014	0.0029	--	0.012	--	--	--	0.0043	0.012	--	0.016
Particulate Solids	41,42,43	0.694	--	0.056	--	0.016	--	--	0.750	--	0.016	0.766
Metal-Framed Filters	26B,52B	0.0017	--	--	0.0086	--	--	--	0.017	0.0086	--	0.010
Total in 55-Gal Drums									2.559	0.114	0.050	2.723
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	0.0035	0.0047	0.0060	0.036	0.012	0.0028	--	0.014	0.036	0.015	0.065
Metal-Framed Filters	25B,26A,26C,45,46,52A, 63B,63C,64	0.017	0.0021	0.0067	0.225	0.013	0.0030	--	0.026	0.225	0.016	0.267
Total in 80-Gal Drums									0.040	0.261	0.031	0.332
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	0.482	--	--	0.482	0.482
Failed Equipment	11B,24,44,51B,62	0.031	0.010	0.021	0.0064	0.0016	0.0032	0.0016	0.061	0.0064	0.0064	0.074
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	0.071	--	--	0.071	0.071
Sample and Analytical Cell (SAC) Waste	23,67	--	--	0.0064	--	0.045	0.010	0.0048	0.0064	--	0.059	0.066
Total in 600-Gal Drums									0.067	0.0064	0.618	0.692
Total All Drums									2.666	0.381	0.699	3.747

(a) Data and stream numbers are taken from Darr (1983).

Note: Volume values obtained from:
(1) Drum/yr from Table 1.
(2) 1500 MTU/yr reprocessing rate.
(3) Volumes occupied by containers as in Darr, p. 28
(a) 55-gal drum occupies 0.258 m^3 (9.1 ft^3)
(b) 80-gal drum occupies 0.351 m^3 (12.4 ft^3)
(c) 600-gal drum occupies 2.41 m^3 (85 ft^3).

TABLE 3.3. Volume of Initial Wastes Before Containerization

		m^3/MTU in Indicated Low-Level Waste Class			m^3/MTU of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
Container Size and Waste Type	Stream Number[a]	A	B	C	<200	$200-10^3$	10^3-10^4	$>10^4$	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	0.0888	--	--	--	--	--	--	0.0888	--	--	0.0888
- Segregated Combustible	27,28,29,47,48,53,65,66	0.976	--	0.130	0.056	0.0113	0.0100	--	1.106	0.056	0.0214	1.183
- Segregated Noncombustible	27,28,29,47,48,53,65,66	0.244	--	0.0326	0.0140	0.00283	0.00251	--	0.276	0.0140	0.00534	0.296
- Total GPT									1.471	0.070	0.0267	1.568
Failed Equipment	11A,51A	0.00070	0.00147	--	0.00944	--	--	--	0.00217	0.00944	--	0.0166
Particulate Solids	41,42,43	0.571	--	0.0410	--	0.00117	--	--	0.612	--	0.0117	0.624
Metal-Framed Filters	26B,52B	0.00030	--	--	0.00283	--	--	--	0.00030	0.00283	--	0.0031
Total in 55-Gal Drums									2.092	0.0823	0.0384	2.212
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	0.00170	0.00138	0.00170	0.0102	0.00347	0.00054	--	0.00478	0.0102	0.00401	0.0190
Metal-Framed Filters	25B,26A,26C,45,46,52A 63B,63C,64	0.00334	0.0068	0.00128	0.0655	0.00363	0.00087	--	0.00531	0.0655	0.00449	0.0753
Total in 80-Gal Drums									0.0101	0.0757	0.0085	0.0943
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	0.425	--	--	0.425	0.425
Failed Equipment	11B,24,44,51B,62	0.0189	0.00740	0.0126	0.00378	0.00094	0.00227	0.00094	0.0389	0.00378	0.0042	0.0468
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	0.0113	--	--	0.0113	0.0113
Sample and Analytical Cell (SAC) Waste	23,67	--	--	0.00153	--	0.0107	0.00629	0.00215	0.00153	--	0.0191	0.0207
Total in 600-Gal Drums									0.0404	0.00378	0.460	0.504
Total All Wastes									2.1425	0.1618	0.507	2.810

(a) Data and stream numbers are taken from Darr (1983).

TABLE 3.4. Weight of Unpackaged Initial Wastes

Container Size and Waste Type	Stream Number[a]	Kg/MTU in Indicated Low-Level Waste Class A	B	C	Kg/MTU of TRU Waste in Indicated Dose Rate (mR/hr) Range <200	$200-10^3$	10^3-10^4	$>10^4$	Totals LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	8.75	--	--	--	--	--	--	8.75	--	--	8.75
- Segregated Combustible	27,28,29,47,48,53,65,66	96.77	--	13.64	6.05	1.18	1.04	--	110.41	6.05	2.22	118.68
- Segregated Noncombustible	27,28,29,47,48,53,65,66	24.19	--	3.40	1.51	0.29	0.26	--	27.59	1.51	0.55	29.65
- Total GPT									146.75	7.56	2.77	157.08
Failed Equipment	11A,51A	1.07	2.27	--	9.33	--	--	--	3.34	9.33	--	12.67
Particulate Solids	41,42,43	354.44	--	72.59	--	20.65	--	--	427.03	--	20.65	447.68
Metal-Framed Filters	26B,52B	0.25	--	--	1.27	--	--	--	0.25	1.27	--	1.52
Total in 55-Gal Drums									577.37	18.16	23.42	618.95
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	0.130	0.173	0.221	1.326	0.451	0.104	--	0.524	1.326	0.555	2.405
Metal-Framed Filters	25B,26A,26C,45,46,52A 63B,63C,64	0.615	0.078	0.247	8.329	0.485	0.113	--	0.940	8.329	0.598	9.867
Total in 80-Gal Drums									1.464	9.655	1.153	12.272
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	324.0	--	--	324.0	324.0
Failed Equipment	11B,24,44,51B,62	11.40	3.60	7.80	2.40	0.60	1.20	0.60	22.80	2.40	2.40	27.60
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	1.32	--	--	1.32	1.32
Sample and Analytical Cell (SAC) Waste	23,67	--	--	0.211	--	1.475	0.316	0.158	0.211	--	1.949	2.16
Total in 600-Gal Drums									23.0	2.40	329.7	355.08
Total All Wastes									601.8	30.2	354.2	986.3

(a) Data and stream numbers are taken from Darr (1983).

TABLE 3.5. Comparison of Wastes Requiring Treatment Before Disposal

Waste	Volume of Initial Waste Packages, m³/MTU					Volume of Waste Before Packaging, m³/MTU	Initial Packaging Factor	Density of Waste Before Packaging, kg/m³
	LLW-B+C	CH-TRU	RH-TRU	Total TRU	Total Requiring Treatment			
Hulls and Hardware	--	--	0.482	0.482	0.482	0.425	0.9	760
Filters	0.0195	0.270	0.102	0.372	0.391	0.102	0.3	130
GPT	0.210	0.093	0.034	0.127	0.337	0.274	0.8	100
SAC	0.0064	--	0.0598	0.0598	0.066	0.021	0.3	100
Failed Equipment	0.034	0.0184	0.0064	0.0232	0.057	0.043	0.8	600-700
Fluorinator Solids	0.056	--	0.016	0.016	0.072	0.0527	0.7	1800
Total	0.326	0.381	0.700	1.08	1.405	0.918		

Note: This table does not include the LLW-A wastes since such wastes do not require any treatment for disposal.

Table 3.6. This uncertainty range, chosen arbitrarily, has relatively little effect on the volume of the various classes of most of the types of waste. However, the fluorinator solids provide a case in which a large variability could occur. The quantity of TRUW of this type could vary from zero to four times the quantity based on the AGNS estimate. This large a variability should be kept in mind when designing and evaluating alternative treatment processes for this waste.

TABLE 3.6. Maximum Possible Variation in Initial Waste Quantities Resulting from Plus or Minus Three-Fold Uncertainties in Radionuclide Contents[(a)]

	Volume of Initial Waste Packages Relative to Reference Case[(b)]				
Waste	LLW-B+C	CH-TRU	RH-TRU	Total TRU	Total Requiring Treatment
Hulls and Hardware	---	---	1.0	1.0	1.0
Filters	0.5 to 1.9	0.8 to 1.0	0.7 to 1.6	0.9 to 1.0	1.0
GPT	0.8 to 3.5	0.7 to 0.8	0.5 to 2.4	0.7 to 1.2	0.8 to 2.6
SAC	0.0 to 1.0	Large	0.4 to 1.0	1.0 to 1.1	1.0
Failed Equipment	1.0 to 1.5	1.0	1.0 to 2.0	1.0 to 1.2	1.0 to 1.4
Fluorinator Solids	0.1 to 1.3	---	0.0 to 4.0	0.0 to 4.0	1.0

(a) Assuming all containers whose classification could be changed in a given direction by a three-fold change in radionuclide were changed in that direction.

(b) Values for the reference case are given in Table 3.5.

4.0 WASTE PROCESSING ALTERNATIVES SELECTION

Five primary waste treatment alternatives were selected for evaluation. In all of the alternatives it is assumed that the high-level liquid waste (HLLW) and the intermediate-level liquid waste (ILLW) are immobilized by vitrification. The primary features of the other reprocessing waste treatment portions of the various alternatives are summarized in Table 4.1. Note that Alternative 5 is divided into options 5a and 5b. More detailed descriptions of each alternative will be presented later.

The waste treatment alternatives selected for study will provide a wide range of treatment process complexity, treated waste volume, and waste form stability. Comparison of the overall waste management system costs for systems involving these alternatives will help to define a minimum-cost reprocessing waste management system and to define the cost impacts of potential waste acceptance criteria and specifications. The five alternatives represent increasing process complexity and waste form stability from Alternative 1 to Alternative 5. Each alternative represents a completely integrated system for the treatment of all wastes except the off-gas treatment wastes, which are unique, small volume wastes that would not affect TRU waste treatment comparisons.

The combination of various possible treatment processes into the alternatives to be examined was based on the objectives of this project, on the relative quantities of the various types of waste, and on other, more subjective, considerations that are addressed later in the report. Assessment of the feasibility and effectiveness of treatment processes was aided by consultation with those involved in a closely related program at PNL sponsored by the Nuclear Waste Treatment Program.

As seen in the data presented in Section 3.3, reprocessing wastes contain LLW as well as TRUW. The level of radioactivity in some of this LLW is low enough that it can be disposed of as LLW-A without additional treatment or packaging. However, other wastes contains too much radioactivity to be disposed of as LLW-A but not enough transuranics to make it TRUW. Such

TABLE 4.1. Reprocessing Waste Treatment Alternative Descriptions

Waste Treatment Alternative No.	Hulls and Hardware	General Process Trash (GPT)		HEPA Filters		Failed Equipment	Fluorinator Solids	SAC[(a)] Waste
		Noncombustible	Combustible	Frame	Media			
1	PWOT[(b)]	PWOT	PWOT	PWOT	PWOT	PWOT	PWOT	PWOT
2	Compact	Compact	Compact	Compact	Compact	PWOT	PWOT	Compact
3	Compact	Compact	Burn and Cement	Burn and Cement	Burn and Cement	PWOT	Cement	Burn and Cement
4	Melt	Melt	Burn and Vitrify w/HLW	As GPT[(c)]	Burn and Vitrify w/HLW	Melt	Cement	Burn and Vitrify/ Melt
5a	Decon	Decon Most, Cement Other	Burn and Vitrify w/HLW	Burn and Cement	Burn and Vitrify w/HLW	Decon Most, Cement Other	Cement	Burn and Vitrify/ Cement
5b	Decon	Decon Most, Melt Other	Burn and Vitrify w/ Other TRU	Burn and Vitrify/ Melt	Burn and Vitrify w/Other TRU	Decon Most, Melt Other	Vitrify w/ Other TRU	Burn and Vitrify/ Melt

---

(a) SAC = Sample and Analytical Cell.
(b) PWOT = Package without treatment.
(c) GPT = General Process Trash.

intermediate wastes (LLW-B and LLW-C) must be treated and/or specially packaged before they can be disposed of as LLW.

Treatment of LLW and TRUW can be interrelated in several ways. Processing of both types of waste through the same facility can affect the unit costs. Some LLW treatment steps can produce additional TRUW (e.g., ash from incineration of combustible LLW). Conversely, some waste treatment steps (e.g., decontamination) can convert a TRUW to a LLW. For these reasons the waste treatment strategies to be described here contain provisions for disposal of the LLW by shallow-land burial as well as of the TRUW by repository disposal. In most alternatives, the low-level wastes are assumed to be treated in the same way as the TRU wastes. Assay facilities will be used to determine the necessary disposal method.

4.1 PACKAGE WITHOUT TREATMENT-ALTERNATIVE 1

In Alternative 1, which is outlined in Figure 4.1, the wastes are retained in their original containers and are disposed of without treatment, except for overpacking the LLW-B and LLW-C in high integrity containers (HICs) so that these wastes meet 10 CFR 61 requirements for shallow-land burial. The 600-gal drum proposed by AGNS may itself be a HIC and not require overpacking; further analysis is necessary to determine whether this is the case. The LLW-A is sent to segregated (from LLW-B and LLW-C) shallow-land burial, and the TRUW is sent to repository disposal, without overpacking in either alternative.

In this alternative, all of the drummed wastes undergo at least exterior inspection before they are assayed to determine their classification. Although x-ray examination of the drum contents may prove to be adequate, it is currently planned that a statistical sample of the drums will also undergo interior inspection to assure that they meet disposal criteria.

It may appear incongruous in this alternative that the TRUW is disposed of with less packaging than are some of the LLW. However, this approach may be justified because of the greatly increased degree of isolation afforded by a geologic repository relative to shallow-land burial. Regardless of whether

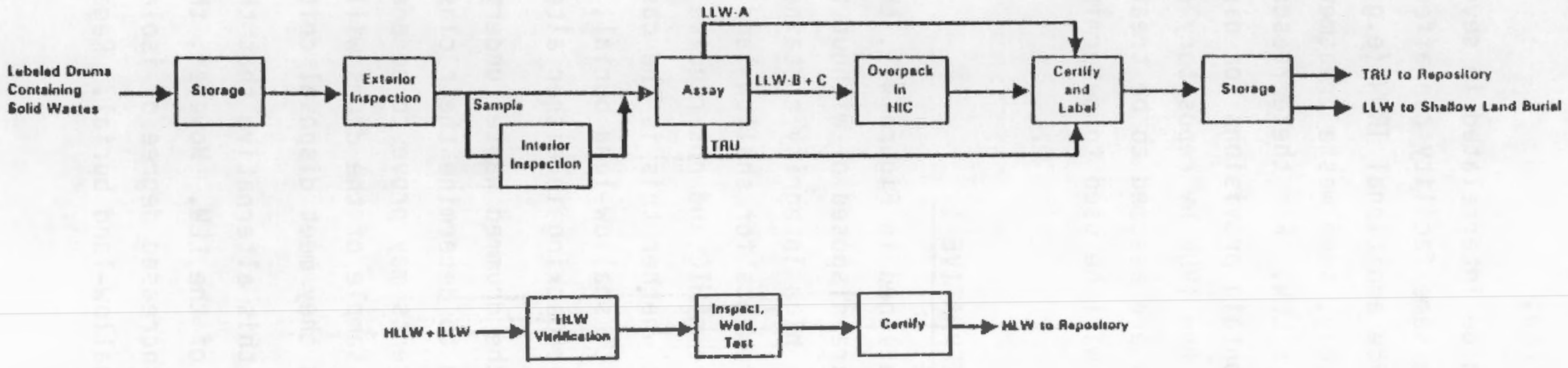

FIGURE 4.1. Alternative 1 Flowsheet-Package Without Treatment

such disposal would be allowed, study of this alternative has value in providing a basis against which to compare the costs and waste form improvements of other alternatives.

Vitrification of the high-level liquid waste (HLLW) and ILLW is also shown in Figure 4.1 for completeness. Even though there is no interaction between this operation and the other waste treatment processes in Alternative 1, the operations are planned to be performed in the same Waste Processing Facility (WPF).

4.2 COMPACTION-ALTERNATIVE 2

Waste treatment Alternative 2 of this study employs compaction to reduce the volume of waste which is sent to disposal. As shown in Figure 4.2, the filters are first shredded so that they can be placed in the compaction canisters. The GPT and SAC wastes are also shredded to improve the compaction efficiency. The hulls and hardware are already small in size, having been sheared prior to addition to the dissolver in the fuel reprocessing plant. The failed equipment and the particulate solids are considered to be relatively noncompactable and are not treated in this alternative; instead they are handled as in Alternative 1. Some additional volume reduction could be achieved by also size-reducing and compacting the failed equipment, but this was not assumed in this alternative. The quantity of failed equipment as defined by Allied-General Nuclear Services is relatively small and a separate size reduction facility did not appear justified.

All of the compactible wastes are processed through one facility. It is assumed that this is done on a campaign basis, and that there is a negligible amount of cross-contamination so that all wastes retain their initial classification unless the classification is altered by the increased concentration achieved by compaction. This is an optimistic assumption, but it is felt that the quantity of waste that would be "degraded" to a higher classification would be minimal in an in-can compaction process as used here. A higher-than-normal surge storage capacity may be required to properly campaign the wastes to meet this objective.

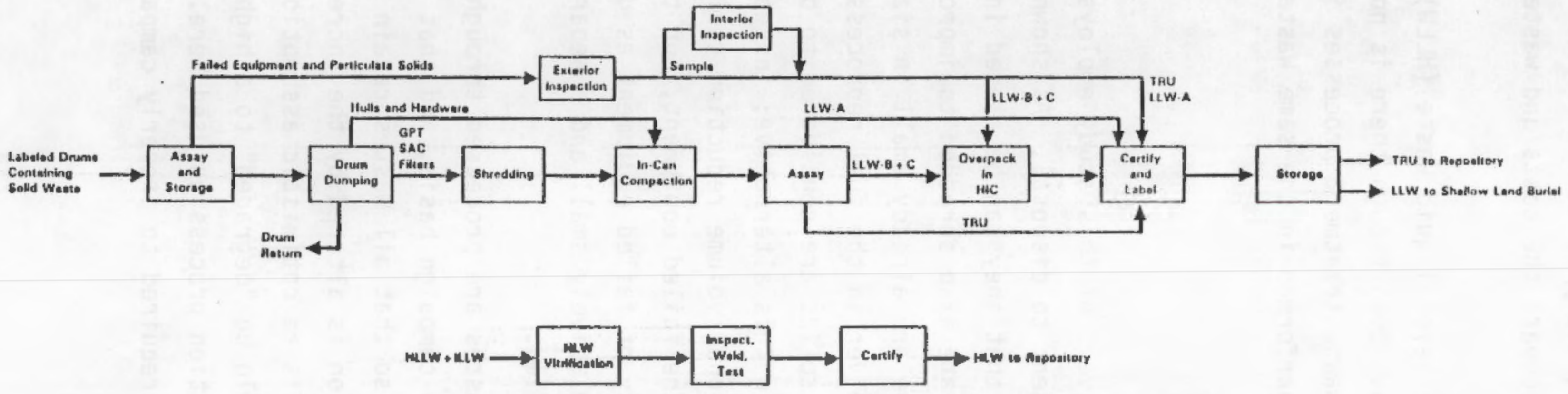

FIGURE 4.2. Alternative 2 Flowsheet-Compaction

The compaction process used in Alternative 2 will give significantly lower waste volumes but little, if any, increase in waste form stability. The LLW-B and LLW-C will still require HIC packaging prior to disposal by shallow-land burial. Separate inspection steps for the compacted wastes are not specified in Figure 4.2 because it is felt that suitable inspection would be a natural part of the activities of a waste treatment facility.

4.3 INCINERATION/CEMENTATION PLUS COMPACTION-ALTERNATIVE 3

In Alternative 3, the treated waste volumes are decreased even more by incinerating the combustible wastes (instead of compacting them), and waste form stability is increased by cementing the incineration residues. As shown in Figure 4.3, the hulls and hardware and the noncombustible GPT are compacted as in Alternative 2. The wastes containing combustible materials (combustible GPT, filters, and SAC waste) are shredded and then incinerated. The ash from the burned combustibles, the filter media, and the shredded metal from the filter frames and the SAC waste are immobilized with cement. The shredded metal could be segregated and compacted with the hulls and hardware, but in this case that possible step was omitted to maintain process simplicity. An aqueous scrubbing operation is included in the incinerator off-gas treatment system to remove acidic gases produced during the combustion of halogenated plastics (e.g., PVC) and rubber. This scrub solution is concentrated and then used as the liquid required in the cementation of the particulate solids and the solid residues resulting from incineration.

In this alternative, as in Alternative 2, the failed equipment equipment is not treated except to package the LLW-B and LLW-C portions for disposal by shallow land burial. The particulate solids that are LLW-B and LLW-C are immobilized with cement in this alternative, and it is assumed that the resultant waste form meets the 10 CFR 61 stability requirements so that HIC packaging is not required. Following cementation, a portion of the drums is opened for inspection to assure that the waste forms meet disposal criteria. Alternately, real time x-ray techniques may provide the necessary assurance.

As in Alternative 2, only one line is assumed for each type of treatment. Because of the radionuclide concentrating action of an incinerator, and

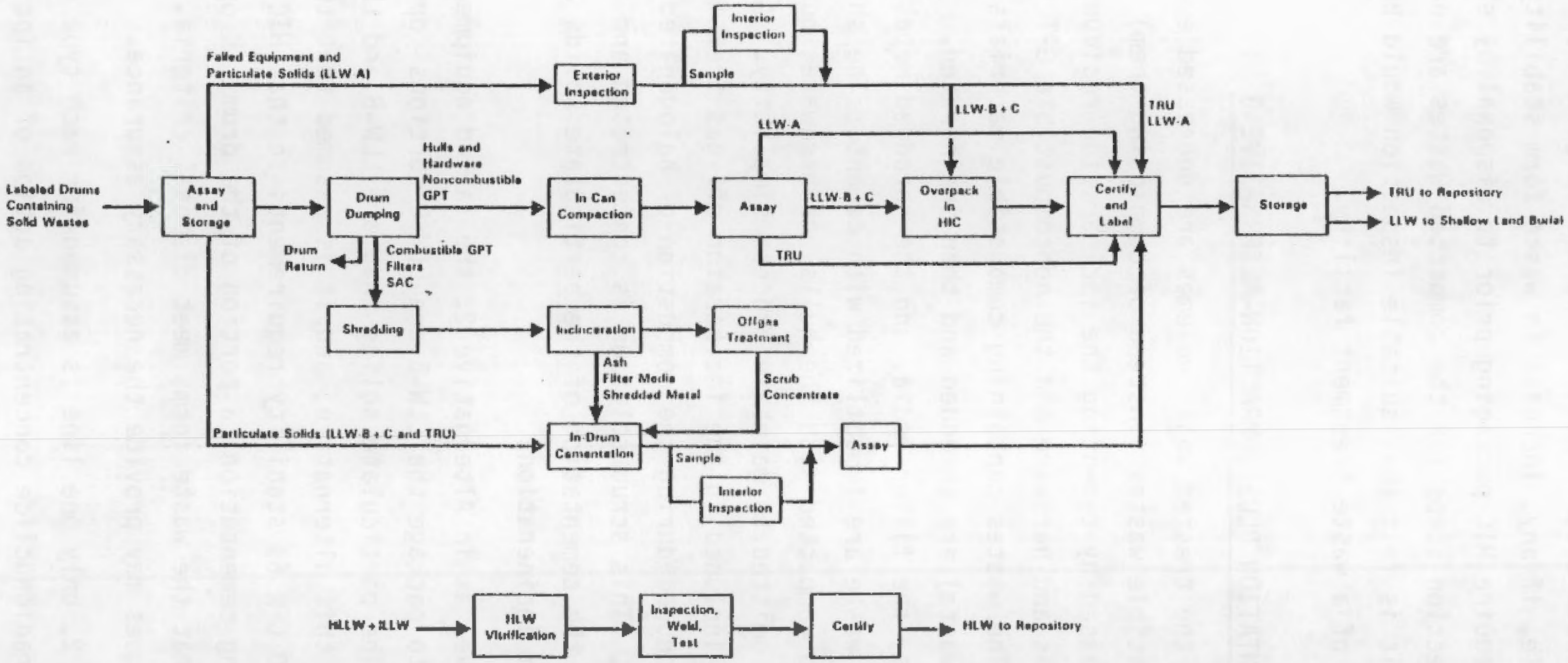

FIGURE 4.3. Alternative 3 Flowsheet-Compaction Plus Inceneration/Cementation

the increased likelihood of cross-contamination in such equipment, it was assumed that all of the solid residues from incineration will be TRU wastes. However, it was also assumed that different waste classifications are campaigned through the incinerator, and that not all of the off-gas scrub concentrate will be TRUW. Thus, a portion of the off-gas scrub concentrate can be used as the liquid required in the cementation of particulate solids without changing the waste classification from LLW to TRUW.

4.4 METALS MELTING PLUS INCINERATION/VITRIFICATION-ALTERNATIVE 4

Waste treatment Alternative 4 of this study, shown in Figure 4.4, provides still greater volume reduction and degree of waste form stability. The metallic wastes are melted instead of being compacted or cemented, and the nonmetallic residues from incineration of the combustible wastes are immobilized in the HLW glass instead of with cement. It is assumed that the incinerator ash contains a small enough fraction of chloride and unburned carbon that it can be added to HLW vitrification without additional treatment. The particulate solids that require treatment before disposal are immobilized by cementation, along with the incinerator off-gas scrub concentrate as in Alternative 3. Because of the high degree of stability of the resultant waste forms, no wastes should require overpacking in HICs in this alternative.

Scrub solution from the melter off-gas treatment system may be cemented or added to the liquids fed to the vitrification process. The melter slag may be disposed of as a separate waste form or it may be included with the cemented wastes. Bulk quantities of slag producing materials (e.g., cement, glass) may be segregated before the melting step for separate packaging or cementation.

4.5 METALS DECONTAMINATION PLUS INCINERATION/VITRIFICATION-ALTERNATIVE 5

In Alternative 5 the effects of decontaminating most of the metallic wastes so that they will require less restrictive disposal are examined. Two different size reduction and decontamination processes are included, one for the hulls and one for other metallic wastes. It is assumed that a fraction of the other metallic wastes is nondecontaminable and is cemented in the primary

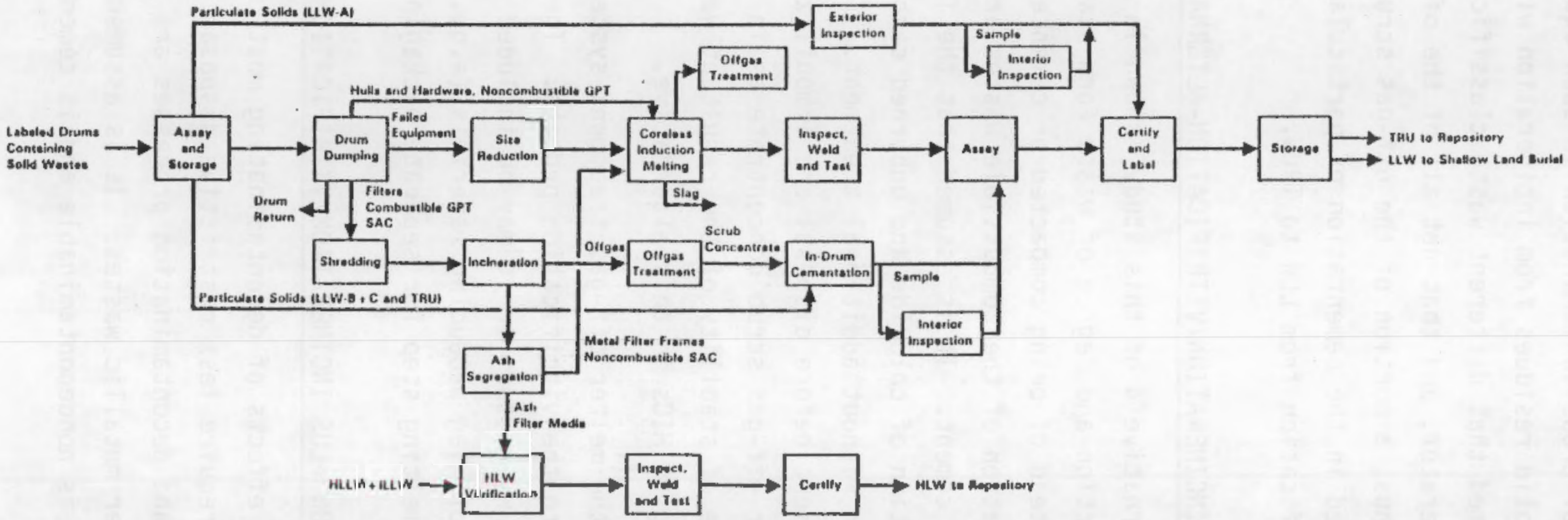

FIGURE 4.4. Alternative 4 Flowsheet-Metals Melting Plus Incineration/Vitrification

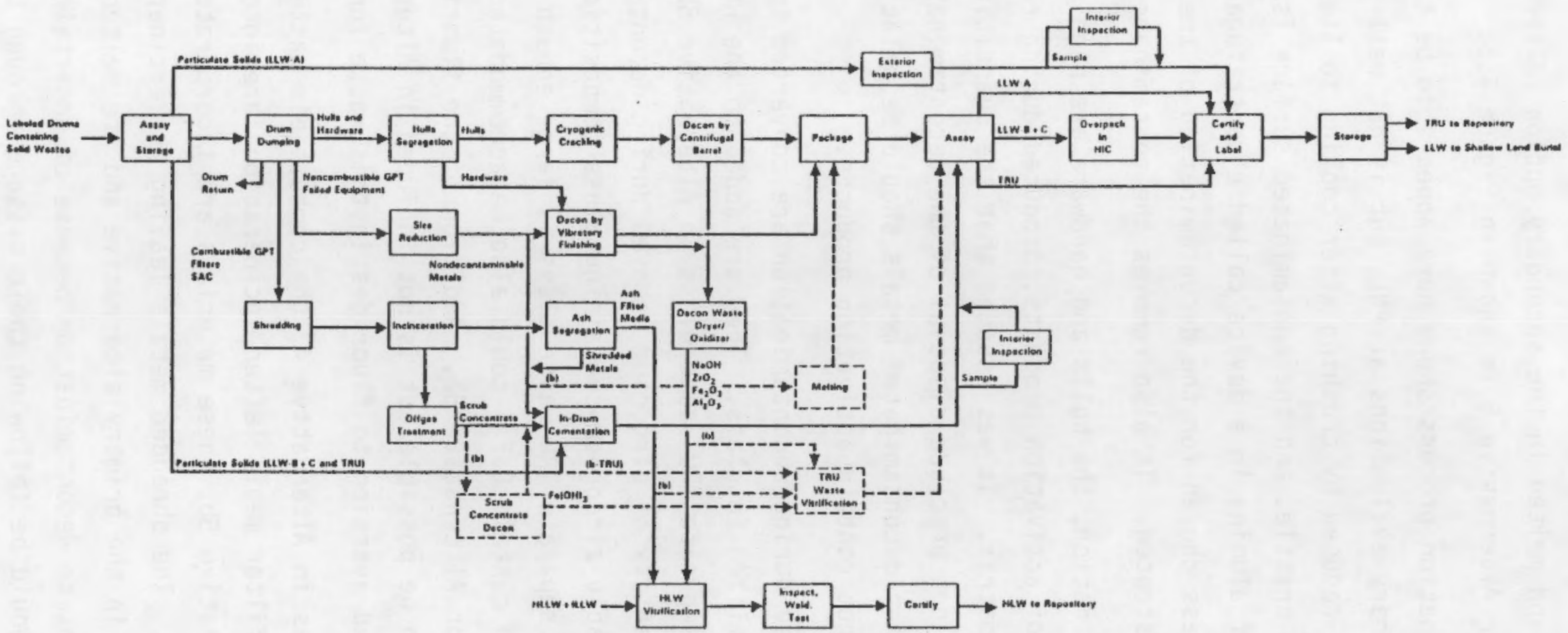

FIGURE 4.5. Alternative 5 Flowsheet-Metals Decontamination Plus Incineration/Vitrification

option (Alternative 5a) and melted in the secondary option (Alternative 5b). The process flowsheet for Alternative 5 is shown in Figure 4.5.

The hulls decontamination process shown here appears to be the most promising, based on preliminary evaluations at PNL, but is not well demonstrated. The hulls are size-reduced by crushing after cooling to liquid nitrogen temperature to make them brittle, and the contaminated surface is then removed by the abrasive action of alumina in a device called a centrifugal barrel. The vibratory finishing process chosen for the decontamination of the other metallic wastes is well demonstrated. It also removes the contaminated surface.

Even after decontamination, the hulls and hardware are highly radioactive because of the presence of activation products, produced during reactor irradiation, within the metal matrix. It was assumed that the quantities of these activation products will not preclude disposal of the decontaminated hulls and hardware as LLW. The other decontaminated metals should be relatively nonradioactive since they do not contain activation products.

The materials removed during decontamination are converted to oxides, as necessary, and are immobilized in glass. They are added to the HLW glass in Alternative 5a and to a separate TRU waste glass in Alternative 5b. Preliminary estimates of the quantity of zirconium removed during decontamination of the hulls, and of a suitable zirconium-containing glass composition, indicate that the quantity of the separate TRU waste glass is large enough that the TRU fluorinator solids (which contain CaF_2) could also be accommodated. This is the procedure selected for Alternative 5b. Addition of the fluorinator solids to the HLW glass may also be possible but is not included in Alternative 5a because of the anticipated aversion to fluorides in this waste form.

In Alternative 5a, as in Alternative 4, the combustible wastes are incinerated and the ash and filter media (after incineration) are incorporated in the HLW glass. In Alternative 5b, these materials are incorporated in the separate TRU waste glass. The shredded metals leaving the incinerator are incorporated with cement in the primary alternative and are melted in Alternative 5b; they are not sent to decontamination because of uncertainties about how decontaminable they would be following their passage through the incinerator.

Another feature of Alternative 5b is that the portion of the incinerator off-gas scrub solution concentrate that is a TRU waste is also decontaminated (by scavenging with ferric hydroxide) before it is cemented. This means that all the cemented products in this alternative should be suitable for disposal by shallow land burial, and no cemented products would be sent to the repository.

5.0 PROCESS AND FACILITY DESCRIPTIONS

The processes and facilities employed in each of the five alternative waste treatment cases considered (see Section 4.0) are briefly described in this section. More detailed descriptions are contained in Appendices A and B.

5.1 PACKAGE WITHOUT TREATMENT (PWOT)-ALTERNATIVE 1

In the PWOT alternative, neither the TRUW nor the LLW receive any treatment; instead, they are disposed of in the containers in which they are packaged at the FRP. However, before these wastes can be disposed of, they must be examined and certified as meeting applicable disposal criteria. This alternative provides the base case against which the costs and hazards of the other alternatives are compared.

To provide a complete waste treatment facility, vitrification of HLLW and ILLW is included and is common to all the cases examined.

5.1.1 Process Description for the PWOT Alternative

A flow diagram for the PWOT alternative is shown in Figure 5.1, with the process stream numbers identified. Table 5.1 contains detail on the quantities of wastes that are present in each of the streams. Since there is no waste treatment, this table duplicates some of the data that were presented earlier in Tables 3.1 through 3.5.

The waste assay, inspection, and certification (WAIC) portions of the process employs two independent lines for waste assay; one for material that is handled remotely and one for material that is handled by contact operations. The waste assay will determine which wastes will be classified as LLW and which as TRUW. The drums are then removed into parallel labeling and surge storage lines--one line for TRUW and one for LLW.

The HLW vitrification portion of the process does not interact with the TRUW and LLW treatment operations in this alternative. It is shown here for comparison with other alternatives where such interaction does occur.

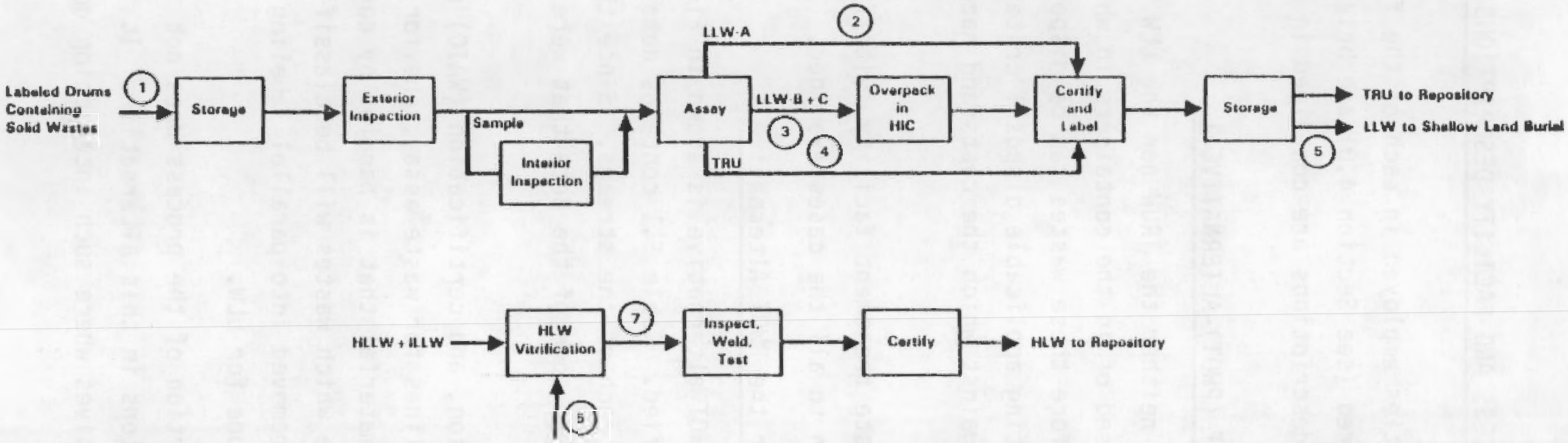

FIGURE 5.1. Alternative 1 Flowsheet-Package Without Treatment

TABLE 5.1. Waste Types and Quantities Present in Each Process Stream--Alternative 1

Waste Type and Quantity (per MTU)	Waste Input 1	LLW-A 2	LLW-B&C 3	TRUW 4	Total LLW 5	Glass-Forming Oxides 6	HLW Glass 7
Hulls and Hardware							
kg	324.0	--	--	324.0	--		
m^3	0.425						
600-gal can	0.200			0.200			
Filters							
kg	15.11	0.995	0.719	13.40	1.714		
m^3	0.1086						
55-gal drum	0.0400	0.0067	--	0.0333	0.0067		
80-gal drum	0.9433	0.0573	0.0553	0.8313	0.1127		
600-gal can	0.0293	--		0.0293	--		
GPT							
kg	157.1	129.7	17.04	10.33	146.7		
m^3	1.568						
55-gal drum	7.480	6.177	0.811	0.492	6.988		
SAC							
kg	2.16	--	0.211	1.949	0.211		
m^3	0.0207						
600-gal can	0.0273	--	0.0027	0.0247	0.0027		
Failed Equipment							
kg	40.27	12.47	13.67	14.13	26.14		
m^3	0.0584						
55-gal drum	0.0633	0.0053	0.0113	0.0467	0.0166		
600-gal can	0.0307	0.0127	0.0127	0.0053	0.0253		
Particulate Solids							
kg	447.7	354.4	72.59	20.65	427.0		
m^3	0.624						
55-gal drum	2.970	2.690	0.218	0.062	2.908		
In-Process Material							
kg	986.3	497.6	104.2	384.4	601.8		
m^3	2.810						
55-gal drum	10.55	8.88	1.04	0.634	9.92		
80-gal drum	0.963	0.057	0.055	0.831	0.112		
600-gal can	0.2873	0.013	0.015	0.259	0.028		
HLW Glass							
kg						191	277
m^3							0.089
60-gal can							0.4633

5.1.2 Facility Description for the PWOT Alternative Case

The Waste Processing Facility (WPF) for the alternative treatment case where the LLW and TRUW are disposed of in the containers in which they were packaged in the reprocessing plant consists of two major components. These are Waste Vitrification Facility, which also includes provisions for storage of the vitrified product, and the Waste Assay, Inspection, and Certification (WAIC) Facility. These two facilities are housed in a structure that will be referred to as WPF-1. Schematic plan drawings of this WPF at several elevations are shown in Figures 5.2 and 5.3. More detailed facility design features are described in Appendix B.

5.1.2.1 Waste Vitrification Facility

Liquid waste vitrification is included in this study, which primarily addresses treatment options for TRUW, because the costs of TRUW treatment facilities are influenced by their colocation with other facilities. In this study it was assumed that TRUW treatment facilities will be colocated with an HLW vitrification facility in a WPF where all waste processing functions are consolidated in one facility. Another reason for considering liquid waste vitrification in this study is that, in some of the alternative TRUW treatment cases, some of the wastes resulting from TRUW treatment are vitrified along with the HLLW and the ILLW.

The waste vitrification process chosen for evaluation uses liquid fed joule-heated, ceramic-melter (LFCM) technology. Two identical 100 percent capacity 1320 kg/day liquid-fed, ceramic-melter units, each with independent canister handling equipment, are included in the facility for process flexibility and dependability. The incoming waste stream is fed directly into the ceramic melter and is calcined and incorporated into a borosilicate glass waste form in a single process step. The molten waste glass is poured into canisters and allowed to cool and solidify. Special provisions are made for preparation of the melter feed and for treatment of off gases from the ceramic melter.

Figures 5.2 and 5.3 show that the facility is divided into two functional operational areas: the process area and the canister storage area. The process area consists of hot cells for containing all of the highly radioactive

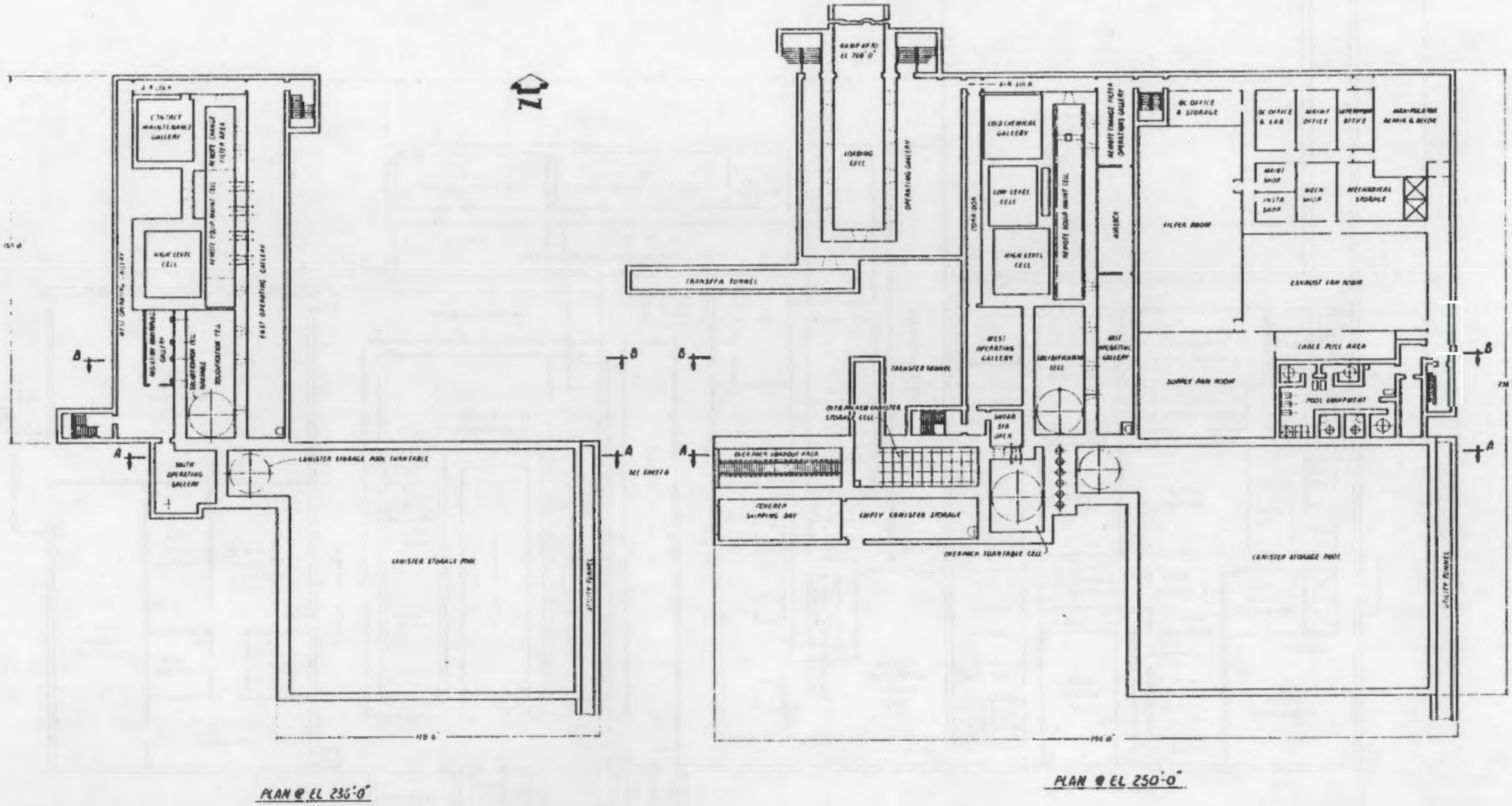

FIGURE 5.2. Schematic of WPF-1

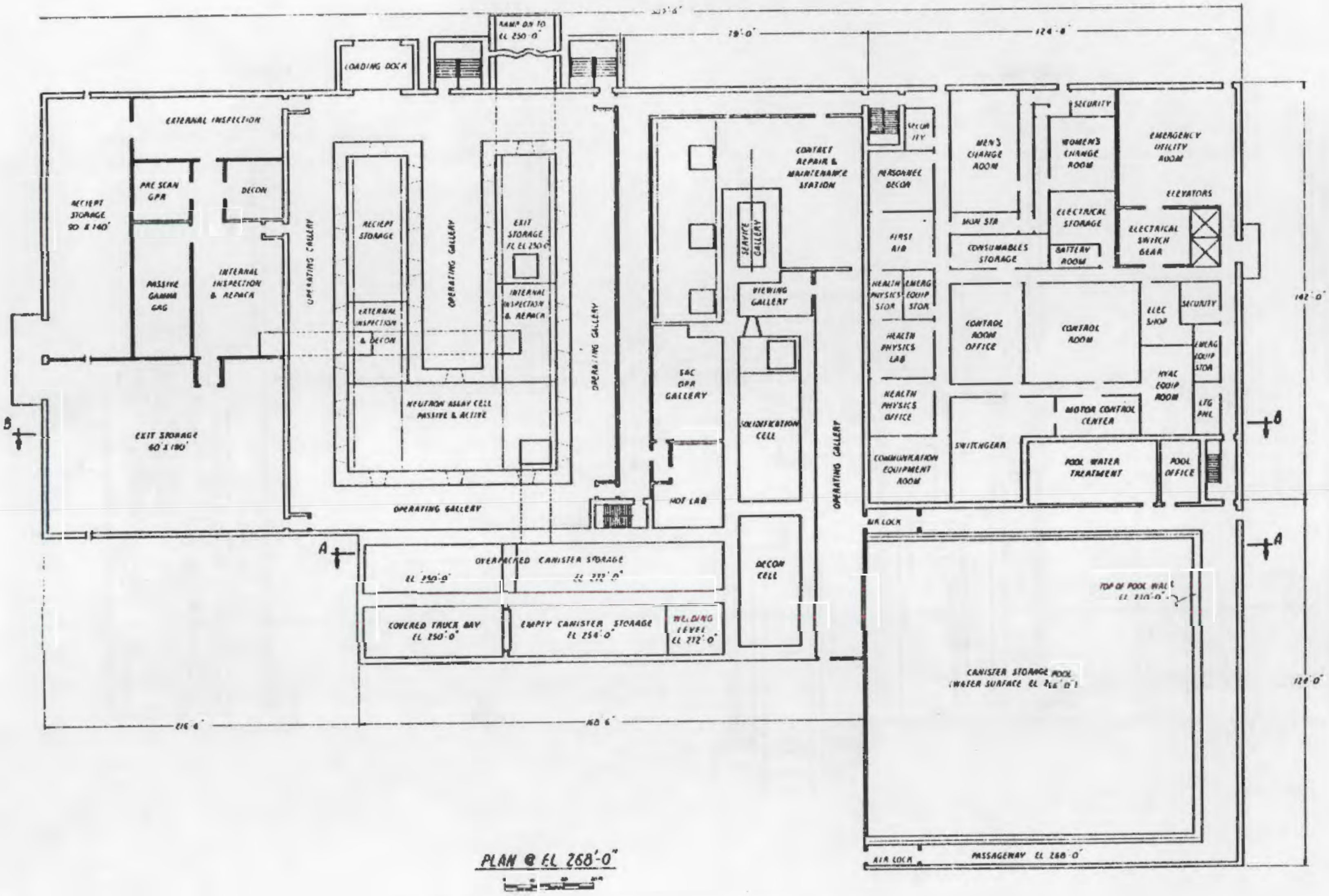

FIGURE 5.3. Plan View of WPF-1

materials, galleries for maintenance and remote manual operation of the adjacent cells, plus laboratories, and offices. The hot cells are designed for remote operation and maintenance. The hot cells in the waste vitrification portion of the WPF are the Solidification Cell, High-Level Cell, Low-Level Cell, Remote Equipment Maintenance Cell, Decontamination Cell, Service Cells, and Sample and Analytical Cells. The cells have galleries adjacent to them. These galleries generally run on both sides of the cells and are appropriately arranged for operation.

The Canister Storage Area consists of a pool capable of storing approximately 1400 waste canisters, a facility for pool water treatment, and an Overpacked Canister Storage Cell. The Canister Storage Pool is located close to the Solidification Cell. The Overpacked Canister Storage Cell is located adjacent to the railroad siding.

5.1.2.2 Waste Assay, Inspection and Certification (WAIC) Facility

The WAIC facility portion of WPF-1 handles both TRU and non-TRU solid wastes that are generated during operation of the FRP. These wastes, which are described in detail in Section 3.0, are received at the WAIC Facility in the containers in which they were packaged at the FRP. The containers, after interim storage at the WAIC Facility, are assayed to determine the classification of the contained waste (e.g., LLW or TRUW and contact handled or remote handled), inspected to assure compliance with disposal regulations, and certified as being in compliance with regulations.

Two independent lines are provided for waste assay; one for material that is handled remotely and one for material that is handled by contact operations. The WAIC facility is this study employs real time x-ray devices to identify the contents of containers. It also includes a gamma prescan to identify low activity wastes, a passive gamma detector for low activity wastes, and active and passive neutron detectors for higher activity wastes. These facilities classify the wastes and identify the quantities of transuranic isotopes present in each waste container. The drums are then removed into parallel labeling and surge storage lines - one line for TRU wastes and one for non-TRU wastes. If a drum is identified as being damaged, the WAIC facility includes a repackaging station. Also included in the WAIC facility is a drum surface decontamination station for drums having excessive surface contamination levels.

About one-month's storage for hulls and other remote-handled containers is included in the neutron interrogation cells. Additional storage for up to a six-month capacity for the receipt and exit of both the remote and the contact-handled drums is provided in the WAIC facility.

Overhead bridge cranes and installed material handling systems will assure adequate semi-remote or remote handling of drums from receiving, through assay, and to shipping or interim storage as required. Provisions are also included for the remote transfer of drums as required between the remote and the contact handled lines. Shielding walls are provided to maintain low dose rates.

5.1.3 Technology Assessment and R&D Needs for the PWOT Alternative

The vitrification process has been under development since 1973 (Daken 1973), and demonstration facilities have been designed. The primary R&D needs of the process will be satisfied once the demonstration facilities are operated successfully.

The primary components of the WAIC facility are the gamma prescan, passive neutron and active neutron detection devices. The gamma prescan and passive neutron techniques are well established and have been successfully applied to TRU wastes (Crane 1980, Close et al. 1983, Caldwell et al. 1983, Brodzinski and Wogman 1978, Wogman et al. 1978).

A number of active neutron detection devices are being developed at the Los Alamos National Laboratory (Kunz et al. 1981, Kunz and Caldwell 1982, Kunz 1983, Caldwell and Kunz 1982), but the ability of these devices monitor TRU waste in 55-, 80- and 600-gal containers has not been fully demonstrated. Additional development work will be necessary to design instruments that can be used in the continuous operating environment of the WPF; and that can handle the various waste materials, quantities and matrices that will be encountered in the facility.

The Oak Ridge National Laboratory has been selected as the site for validation studies of the Neutron Interrogation Assay System (NIAS) developed at Los Alamos National Laboratory (Beauchamp et al. 1983, Schultz et al. 1983).

These demonstration tests will be conducted with TRU waste contained in 55-gal drums. Such systems are also being used at other DOE sites.

As the capabilities of the NIAS assay equipment are demonstrated, the precision and accuracy of the device will be defined. This definition is necessary so that assay facilities can be designed to provide all of the information necessary to assure compliance with applicable certification requirements.

5.2 COMPACTION-ALTERNATIVE 2

This waste treatment alternative includes provisions for compaction of fuel cladding hulls and hardware and other compactable wastes. This process provides volume reduction but does not improve the waste form stability. Other wastes are handled as in the PWOT alternative.

5.2.1 Process Description for the Compaction Alternative

The process streams are identified Figure 5.4, and Table 5.2 provides detailed quantities of the materials present in the different streams.

The compaction process employs a vertical hydraulic ram to compact many of the wastes in 22-in. diameter by 8-ft long (160 gal) carbon steel canisters for shipment to disposal. As shown in Figure 5.4, some of these wastes are shredded before compaction. This step is necessary for the filters since they would not otherwise fit within the canisters, and it also improves the compaction efficiency for the other wastes.

5.2.2 Facility Description for the Compaction Alternative

The Waste Processing Facility (WPF-2) for this alternative case contains a compaction facility as well as WAIC and waste vitrification facilities like those present in WPF-1. A schematic plan drawing of WPF-2 is contained in Figure 5.5. The shaded portion of this drawing denotes the portion of the building that is the same size as in WPF-1. More details are given in Appendix B.

The vitrification facilities are identical to those in Alternative 1. However, the WAIC facility operation in WPF-2 is slightly different from that in WPF-1 in that more containers must be assayed, but fewer containers must be

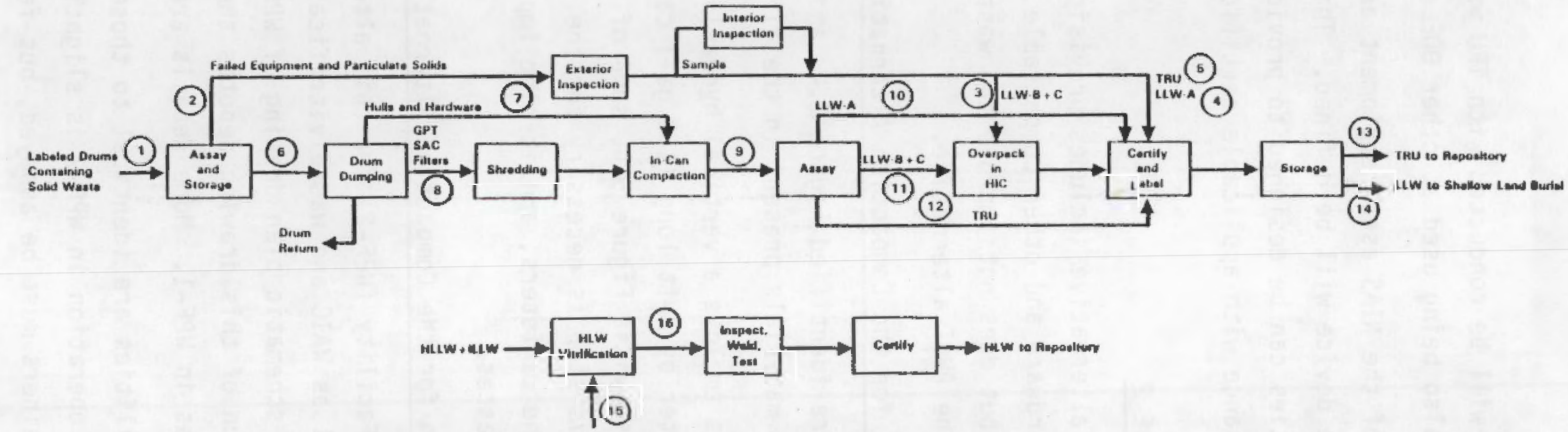

FIGURE 5.4. Alternative 2 Flowsheet-Compaction

TABLE 5.2. Types and Quantities of Wastes Present in Each Process Stream--Alternative 2

Waste Type and Quantity (per MTU)	Waste Input 1	PWOT Waste 2	PWOT LLW-B&C 3	PWOT LLW-A 4	PWOT TRUW 5	Waste to be Treated 6	Direct Feed to Compactor 7	Shredder Feed 8	Compacted Waste (Total) 9	Compacted LLW-A 10	Compacted LLW-B&C 11	Compacted TRUW 12	Total TRUW 13	Total LLW 14	Glass-Forming Oxides 15	Vitrified HLW 16
Hulls and Hardware																
kg	324.0	--	--	--	--	324.0	324.0	--	324.0	--	--	324.0	324.0	--		
m^3	0.425															
160-gal can	--								0.2363			0.2363	0.2363			
600-gal can	0.200					0.200	0.200		--			--	--			
Filters																
kg	15.11	--	--	--	--	15.11	--	15.11	15.11	0.990	0.719	13.40	13.40	1.709		
m^3	0.1086															
55-gal drum	0.0400								--	--	--	--	--	--		
80-gal drum	0.9633								--	--	--	--	--	--		
160-gal can	--								0.0501	0.00238	0.00265	0.04507	0.04507	0.00503		
600-gal can	0.0243								--	--	--	--	--	--		
GPT																
kg	157.1	--	--	--	--	157.1	--	157.1	157.1	129.7	17.04	10.33	10.33	146.7		
m^3	1.568															
55-gal drum	7.480								--	--	--	--	--	--		
160-gal can	--								0.9084	0.7561	0.0957	0.05665	0.05665	0.8518		
SAC																
kg	2.16	--	--	--	--	2.16	--	2.16	2.16	--	0.211	1.949	1.949	0.211		
m^3	0.0207															
160-gal can	--								0.01482		0.00109	0.01373	0.01373	0.00109		
600-gal can	0.0273								--		--	--	--	--		
Failed Equipment																
kg	40.27	40.27	13.67	12.47	14.13	--	--	--	--	--	--	--	14.13	26.14		
m^3	0.0584															
55-gal drum	0.0633	0.0633	0.0113	0.00533	0.0467								0.0467	0.0166		
600-gal can	0.0307	0.0307	0.01267	0.01267	0.00533								0.00533	0.0253		
Particulate Solids																
kg	447.7	447.7	72.59	354.4	20.65	--	--	--	--	--	--	--	20.65	427.0		
m^3	0.624															
55-gal drum	2.970	2.970	0.218	2.690	0.062								0.062	2.908		
In-Process Material																
kg	986.3	488.0	86.26	366.9	34.78	498.4	324.0	174.4	498.4	130.7	18.0	349.7	384.5	501.8		
m^3	2.810															
55-gal drum	10.55	3.033	0.229	2.695	0.109								0.109	2.925		
80-gal drum	0.943	--	--	--	--								--	--		
160-gal can	--	--	--	--	--	--			1.210	0.7585	0.0994	0.3518	0.3517	0.8579		
600-gal can	0.2873	0.0307	0.0127	0.0127	0.0053								0.00533	0.0253		
HLW Glass																
kg															191	277
m^3																0.089
60-gal can																0.4633

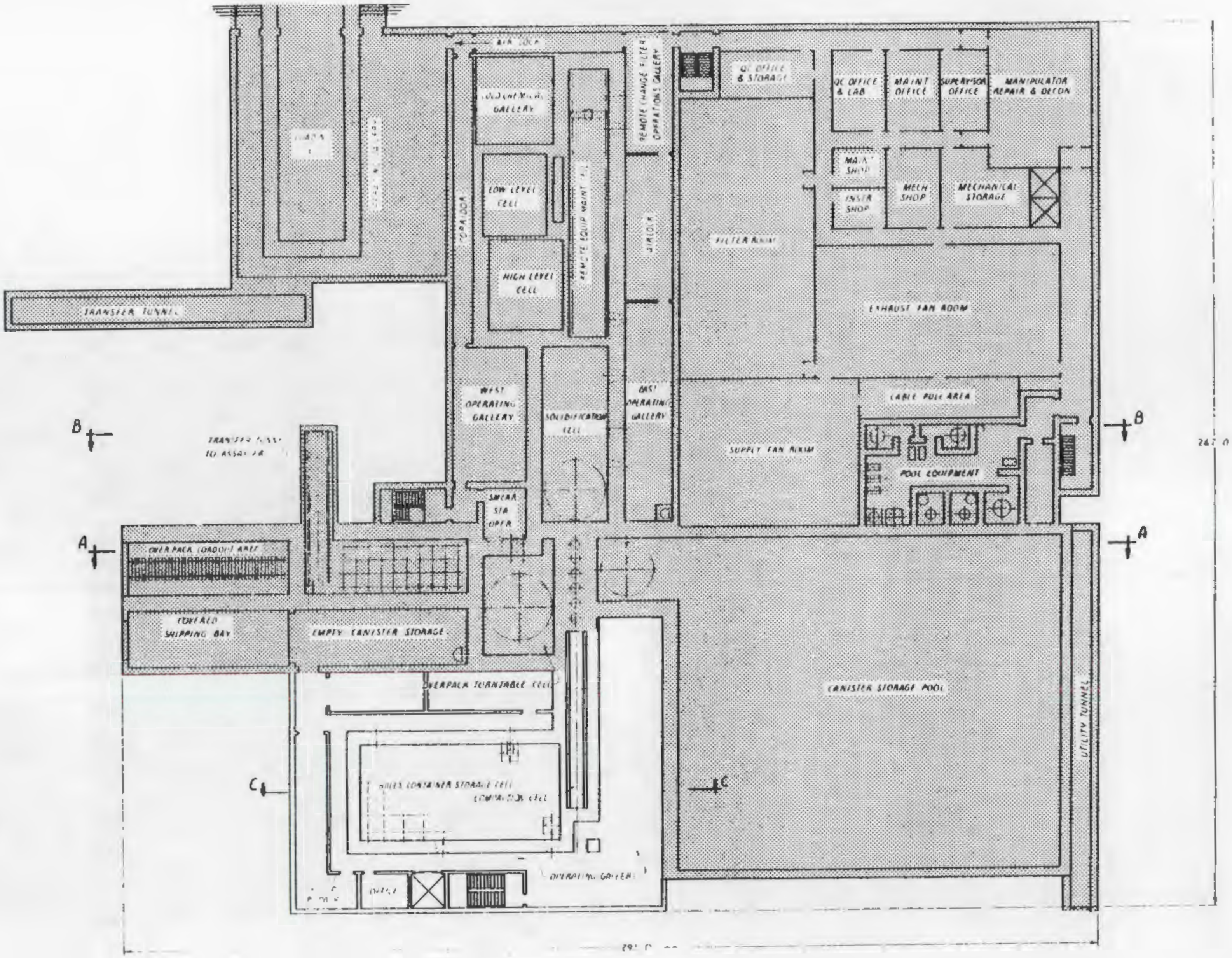

FIGURE 5.5. Plan View of WPF-2

certified and stored awaiting shipment. The overall space requirements are the same, except that smaller exit storage facilities are required in WPF-2.

The design of the waste compaction facility follows the general concept used in the other parts of the WPF including: 1) facilities for receiving and shipping process materials; 2) facilities and equipment for transferring process material to other processes as required; 3) hot cells with supporting services and galleries for operation and maintenance; and 4) facilities for associated activities that are not required to be performed remotely.

The facility will be constructed of normal density concrete. Most cell walls will be 3 to 4 ft thick. The first floor of the facility will be underground and all external walls will be at least 18 in. thick to support soil loadings.

The cold compaction process is basically a batch-type operation that consists of a number of mechanical operations and transfers and very minimal chemical processing or changes (Anderson et al. 1979). In addition, very little off gas is generated. The process utilizes a compactor in a vertical position. It is designed for a 8 ft, 11 in. stroke, 3000 psi cylinder pressure, 10,000 psi developed compaction pressure, and 4.5×10^6 lb total force. The wastes are compacted in 22 in. diameter x 8 ft long (160 gal) carbon steel canisters. The canisters are welded shut and tested before they are shipped to disposal. More details of the facility structure and equipment are contained in Section 8.2.3.

5.2.3 Technology Assessment and R&D Needs for the Compaction Alternative Case

The size reduction of LLW by hammermills and knife shredders has been considered for the past ten years (AI 1973). However, sealed transuranic waste drums may contain explosive concentrations of hydrogen, resins and other materials that could cause fires and/or minor explosions. These characteristics are not compatible with the pulverizing action existent in hammermills and high speed shredders. As a result, low speed shredders have received the most attention as a means of reducing the size of solid LLW and TRUW (Ziegler et al. 1973).

Recently, an extensive series of waste shredability tests was conducted at the Idaho National Engineering Laboratory (Darnell and Aldrich 1983). The major objective of the test was to prove that low speed shredders could be used to simultaneously open drums and boxes containing TRUW while shredding the waste contents. The tests were successful. Fifty-five gal drums containing combustibles, angle iron, steel plate, old typewriters, pipes and other items were shredded by low speed (less than 60 rpm) units with dual counter-rotating shafts. The investigators concluded that shredders will be able to shred the waste anticipated in the TRU Waste Treatment Facility (TWTF) at the Idaho National Engineering Laboratory (INEL) to an acceptable size, with sufficient throughput (up to 45 ton/day), at a low power consumption (less than 80 hp), in a remote environment, and with reasonable maintenance requirements.

The compaction process has not been tested. The actual compaction pressure versus degree of compaction relationships for GPT, SAC, HEPA filters, and hulls and hardware will have to be determined empirically.

The operability of low speed shredders and cold compactors in a remote environment remains to be demonstrated to provide additional information about maintenance requirements, operating procedures, and control systems. Large-scale functional operational tests must verify that fires (from Zircaloy fines that occur as new nonoxidized surfaces are exposed during compaction) will not be induced by the high pressures and forces present in the system, since the fines may be pyrophoric.

The use of repository canisters as compaction containers may cause the canister walls to deflect substantially, reducing the ultimate integrity of the canister (Anderson and Evans 1983). The effects of compaction pressure on canister integrity will have to be quantified, as well as the use of an external rigid structure to minimize wall deflection.

5.3 COMPACTION PLUS INCINERATION/CEMENTATION

For the third waste treatment concept, combustible wastes are incinerated and other compactable, but noncombustible, wastes are compacted. This treatment results in a more stable waste form for combustible wastes and provides a basis for determining the impact of excluding combustible materials from a repository. An overall waste volume reduction is also realized for this case. The ash and scrubber solution from incineration and the particulate solids that are not LLW-A are immobilized with cement. The LLW-A particulate solids and the failed equipment are handled as in the PWOT alternative.

5.3.1 Process Description for the Incineration/Cementation Plus Compaction Alternative Case

The process for this waste treatment alternative was described in Section 4.3. Figure 5.6 identifies the process streams, and Table 5.3 supplies the quantities present in the different streams.

In this process, combustible wastes are incinerated in a dual chamber controlled air incinerator using a mixture of natural gas and air. The off gas is cooled, scrubbed to remove particulate material and acidic vapors, and the scrubber solution is concentrated by evaporation. This concentrated scrubber solution is used as the aqueous ingredient in formulating the cement mixture used to immobilize the incinerator ash and the particulate solids other than those that are LLW-A.

The compaction, vitrification, and WAIC operation use the same processes as in the compaction alternative.

5.3.2 Facility Description for Incineration/Cementation Plus Compaction Alternative

The waste processing facility (WPF-3) for this alternative contains incineration and cementation facilities in addition to WAIC, waste vitrification, and compaction facilities as were present in WPF-2. A schematic plan drawing of WPF-3 is contained in Figure 5.7. As before, the shaded portion of the drawing denotes the portion of the building that is the same size as in WPF-1. More details are given in Appendix B.

The compaction facility in WPF-3 is smaller than that in WPF-2 due to lower waste throughput (some wastes that were previously compacted are incinerated). Also, the compaction facility in WPF-3 does not contain the shredder that was used in WPF-2. The vitrification facility in WPF-3 is identical to that in WPF-1 and WPF-2, and the WAIC facility is comparable to that in WPF-2.

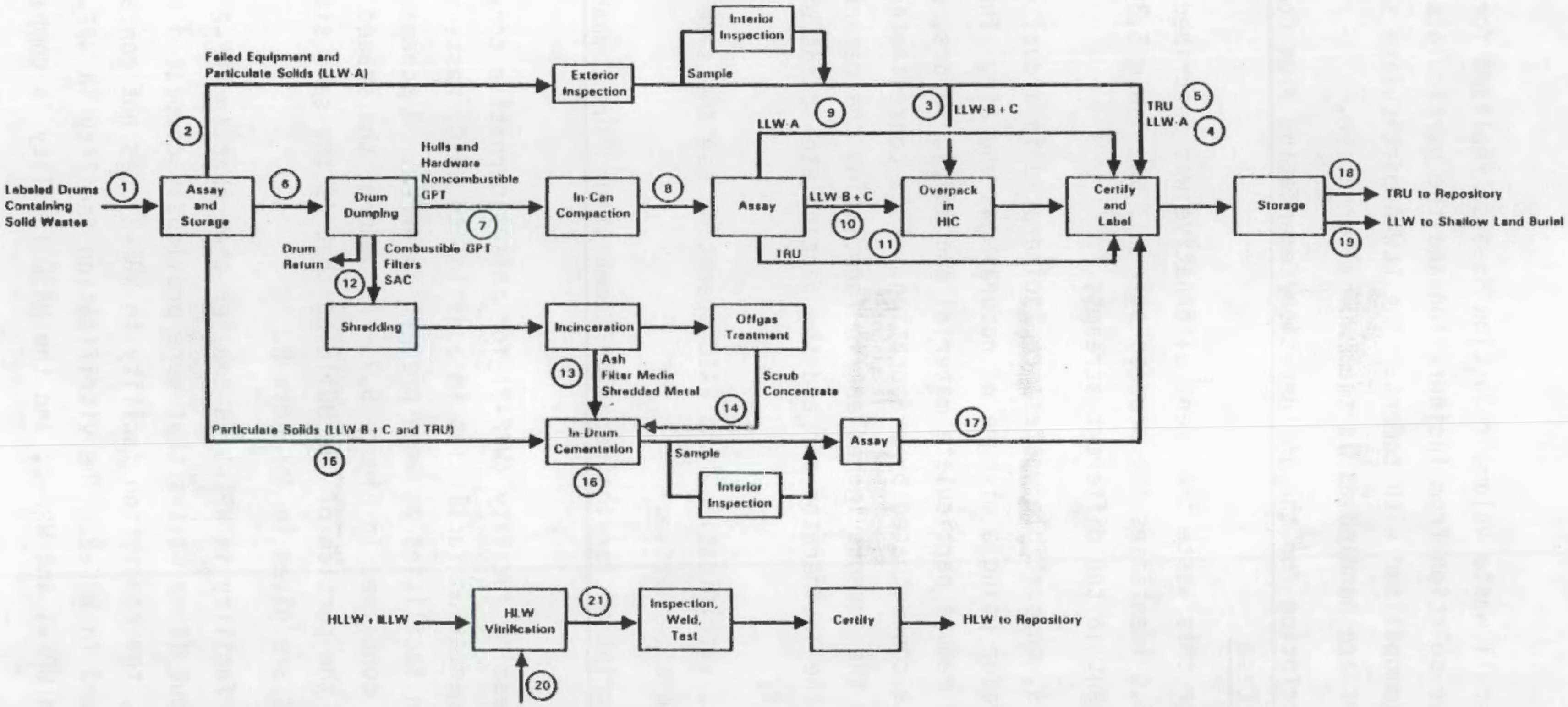

FIGURE 5.6. Alternative 3 Flowsheet-Incineration/Cementation Plus Compaction

TABLE 5.3. Waste Types and Quantities Present in Each Process Stream--Alternative 3

Waste Type and Quantity (per MTU)	Waste Input 1	PWOT Waste 2	PWOT LLW-B&C 3	PWOT LLW-A 4	PWOT TRUW 5	Compaction or Inciner-ation Feed 6	Compaction Feed 7	Compacted Waste (Total) 8	Compacted LLW-A 9	Compacted LLW-B&C 10	Compacted TRUW 11	Shredder Feed 12	Incineration Residue 13	Offgas Scrub Concentrate 14	Particulate Solids To Be Treated 15	Cement 16	Cemented Waste 17	Total TRUW 18	Total LLW 19	Glass-Forming Oxides 20	Vitrified HLW 21
Hulls and Hardware																					
kg	324.0	--	--	--	--	324.0	324.0	324.0	--	--	324.0	--	--	--	--	--					
m^3	0.425																				
160-gal can	--					--	--	0.2363			0.2363										
600-gal can	0.200					0.200	0.200	--			--										
Filters																					
kg	15.11	--	--	--	--	15.11	--	--	--	--	--	15.11	9.448		--	--					
m^3	0.1086													--							
55-gal drum	0.0400					0.0400						0.0400									
80-gal drum	0.9433					0.9433						0.9433									
600-gal can	0.0293					2.0293						0.0293									
GPT																					
kg	157.1	--	--	--	--	157.1	29.65	29.65	24.19	3.40	2.06	127.4	4.247		--	--					
m^3	1.568																				
55-gal drum	7.480					7.480	1.4127	--	--	--	--	6.067									
160-gal can	--					--		0.3249	0.2679	0.0358	0.0212	--									
SAC																					
kg	2.16	--	--	--	--	2.16	--	--	--	--	--	2.16	0.9026		--	--					
m^3	0.0207																				
600-gal can	0.0273					0.0273						0.0273									
Failed Equipment																					
kg	40.27	40.27	13.67	12.47	14.13	--	--	--	--	--	--	--	--	--	--	--					
m^3	0.0584																				
55-gal drum	0.0633	0.0633	0.0113	0.00533	0.0467																
600-gal can	0.0307	0.0307	0.01267	0.01267	0.00533																
Particulate Solids																					
kg	447.7	354.4	--	354.4	--	--	--	--	--	--	--	--	--	--	93.24	--					
m^3	0.624																				
55-gal drum	2.970	2.690	--	2.690	--										0.280						
In-Process Material																					
kg	986.3	394.7	13.67	366.9	14.13	498.4	353.6	353.6	24.19	3.408	326.6	144.7	14.60		93.24	121.6	374.7				
m^3	2.810																				
55-gal drum	10.55	2.753	0.0113	2.695	0.0467	7.520		--	--	--	--				0.280		0.8081	0.5231	3.239		
80-gal drum	0.943	--	--	--	--	0.943									--		--	--	--		
160-gal can	--	--	--	--	--	--		0.5612	0.2679	0.0358	0.2575				--		--	0.2575	0.3038		
600-gal can	0.2873	0.0307	0.01267	0.01267	0.00533	0.0566		--	--	--	--				--			0.00533	0.02533		
HLW Glass																					
kg																				191	277
m^3																					0.089
60-gal can																					0.4633

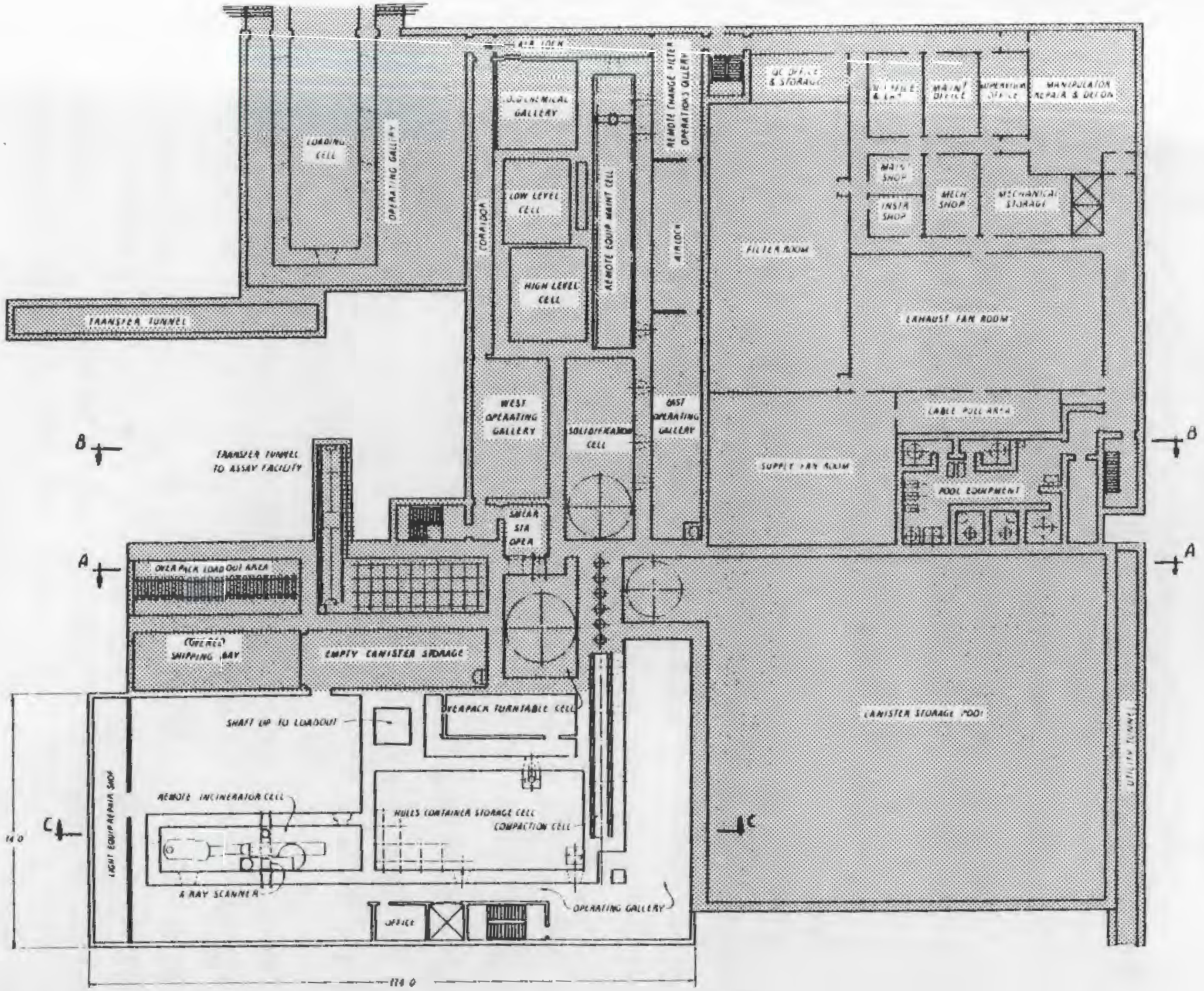

FIGURE 5.7. Plan View of WPF-3

The heart of the incineration/cementation facility is a dual-chamber, controlled-air incinerator where the combustible portions of the wastes are burned. The incinerator off gases are passed through an off-gas system containing a wet scrubber to remove acidic combustion products and filters to remove particulates. The wet scrubber solution, which contains primarily sodium chloride, is concentrated before it is cemented for disposal.

In-drum cementation equipment is also included in this facility. Appropriate quantities of cement, water (or scrubber solution), and solid wastes are measured into drums, which are then capped and tumbled to mix the components so that a monolithic solid waste form results when the cement has cured. The wastes processed through cementation include some of the particulate solid wastes produced at the FRP, in addition to the liquid and solid wastes generated during the incineration process.

Another major piece of equipment in the incineration/cementation facility is a shredder, which is especially important in size-reducing HEPA filters so that they can be fed to the incinerator. The shredder in this facility is very similar to that used in the compaction facility of WPF-2, but which is not needed in the compaction facility of WPF-3.

5.3.3 Technology Assessment and R&D Needs for Incineration/Cementation

The performance of a controlled air incinerator (CAI) has been evaluated at Los Alamos National Laboratory (LANL) since 1978. The CAI has been tested with TRUW and LLW since 1980. The process is sized for a process rate of 45 kg/hr, has operated for approximately 2000 hr, and has processed about 500 kg of LLW and TRUW since 198D.

The CAI developed at LANL was chosen as the incineration system for this preconceptual evaluation. The decision criteria were subjective and based on simplicity and lower expected off-gas particulate loadings. An objective evaluation awaits coincident test burns by this and other incinerator designs on the same feed mixture.

All incinerator systems will discharge gaseous and solid effluents. Effluents in the off gas are removed by an appropriately designed off-gas cleaning system (Hedahl 1982a). The CAI off-gas system employs a quench column, venturi scrubber, packed column, condenser, demister, reheater, and a series arrangement of HEPA filters to control gaseous and solid effluents (Coplan 1982). The existing CAI system at LANL does not aim to concentrate scrub solution blowdown. The concentration of blowdown solution using evaporators remain to be demonstrated.

Cementation processes have been used for the disposal of low and intermediate level wastes since before 1968 (ERDA 1976a). The use of the in-drum cementation process for incinerator ash has been demonstrated at the Savannah River Laboratory (SRL). However, concentrated scrubber solution was not used in this demonstration.

The residue removed from the incinerator will consist of metal fragments and other aggregates of various sizes as well as more finely divided ash. The addition of such materials to cement can create void spaces in the cured cement matrix. A recent series of runs with incinerated simulated transuranic waste materials indicated that void spaces can be reduced if incinerator ash is segregated by size prior to cementation (Pattengill et al. 1983). The need for ash segregation by size, and the detailed design of a system awaits demonstration tests with incinerated TRU ash and particulate solids.

The incineration and cementation processes have been evaluated and applied to LLW and TRUW (ERDA 1976b, Coplan 1982, Klingler 1983, Garcia 1983, Hedahl 1982a, Hedahl 1982b, "47" 1976, Ross et al. 1982, Schneider and Lederbrink 1982, Pattengill 1983). However, the processes must still be demonstrated on the waste streams anticipated for the WPF.

Tests of various incinerator types should continue. Test burns using a simulated BNFP LLW and TRUW feeds would help identify the most applicable technology for this waste.

The cementation process must be demonstrated with concentrated scrub solution, incinerator ash and particulate solids. Operating variables (waste/cement ratio, scrub solution volume, ash size segregation, degree and type of agitation) must be optimized, and the stability of the waste form produced must also be quantified.

5.4 METALS MELTING PLUS INCINERATION/VITRIFICATION-ALTERNATIVE 4

In this waste treatment concept the metallic wastes are melted to reduce the volume as much as possible and also to produce a more stable waste form. As in the previous concept, combustible wastes are incinerated; however, in this concept the nonmetallic solid incineration residues are immobilized by vitrification in the HLW glass. This provides greater waste form stability than the cementation process used for this waste stream in the compaction plus incineration/cementation alternative, which was discussed in Section 5.3. Cementation is also included in this concept for some of the less radioactive waste streams.

5.4.1 Process Description for the Metals Melting Plus Incineration/Vitrification Alternative

The process for this waste treatment alternative was described in Section 4.4. Figure 5.8 shows a flow diagram of this process and Table 5.4 identifies the quantities present in the different streams.

In this process, all of the metallic wastes are melted together. The major waste component, the hulls and hardware, and the noncombustible GPT are fed directly to the melter while the failed equipment is first size-reduced (as required). This treatment alternative is the first one where failed equipment is treated. Other metallic wastes pass first through the incinerator and are segregated from the other solid incineration residues before going to the melter.

The shredding and incineration of the combustible wastes proceeds as in the previous alternative, as does the cementation of the concentrated off-gas scrubber solution and the particulate solids from the FRP. The incinerator ash and filter media are fed to the HLW vitrification process where they take the place of some of the added glass-forming chemicals. The vitrification process is otherwise the same as in the preceding alternatives.

5.4.2 Facility Description for the Metals Melting Plus Incineration/Vitrification Alternative

The waste processing facility for this alternative, WPF-4, contains WAIC and HLW vitrification facilities as in the previous three cases, an

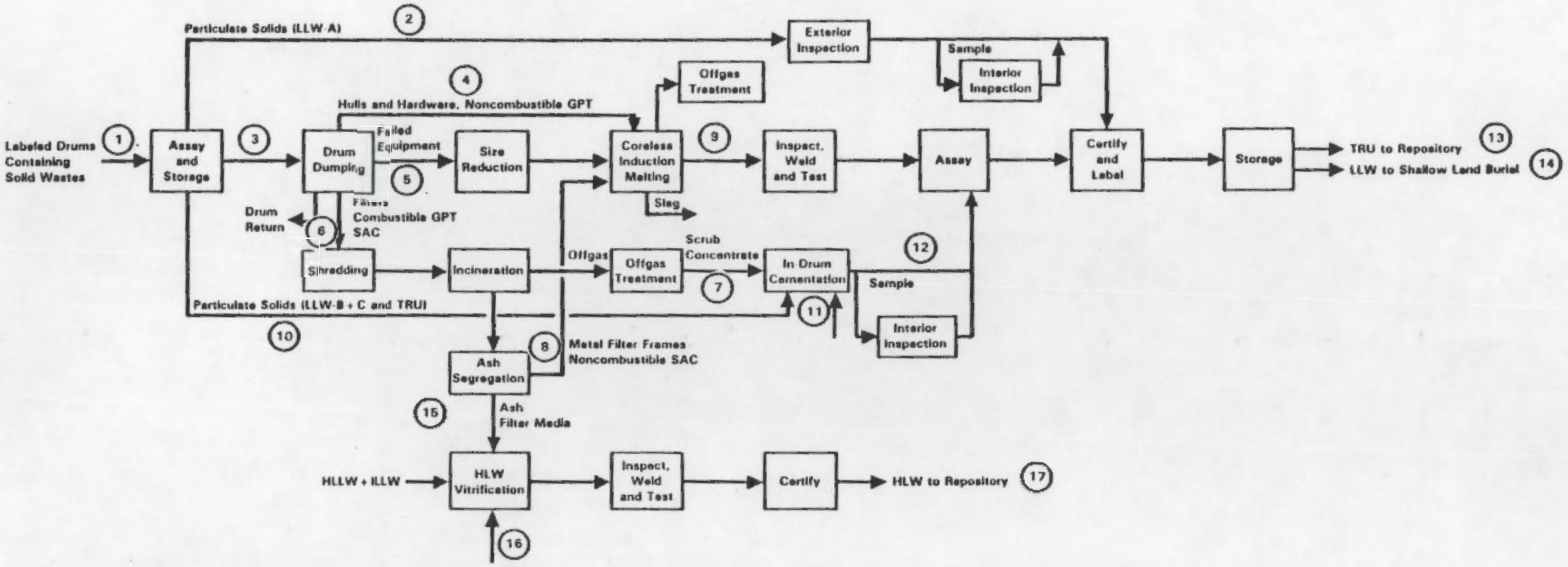

FIGURE 5.8. Alternative 4 Flowsheet-Metals Melting Plus Incineration/Vitrification

TABLE 5.4. Waste Types and Quantities Present in Each Process Stream--Alternative 4

Waste Type and Quantity (per MTU)	Waste Input 1	PWOT Waste 2	Melting or Incineration Feed 3	Direct Feed to Melter 4	Feed to Size Reduction 5	Shredder Feed 6	Offgas Scrub Concentrate 7	Mettalic Incineration Residue 8	Melted Metals 9	Particulate Solids 10	Cement 11	Cemented Waste 12	Total TRUW 13	Total LLW 14	Nonmetallic Incineration Residue 15	Glass-Forming Oxides 16	Vitrified HLW 17
Hulls and Hardware																	
kg	324.0	--	324.0	324.0	--	--	--	--	324.0	--					--		
m^3	0.425																
160-gal can	--																
600-gal can	0.200		0.200	0.200													
Filters																	
kg	15.11	--	15.11	--	--	15.11	--	4.24	4.24	--					5.213		
m^3	0.1086																
55-gal drum	0.0400		0.0400			0.0400											
80-gal drum	0.9433		0.9433			0.9433											
600-gal can	0.0293		0.0293			0.0293											
GPT																	
kg	157.1	--	157.1	29.65	--	127.4		--	31.40	--					3.809		
m^3	1.568						0.0724										
55-gal drum	7.480		7.480	1.4127		6.067											
SAC																	
kg	2.16	--	2.16	--	--	2.16		0.863	0.863	--					0.039		
m^3	0.0207						0.00074										
600-gal can	0.0273		0.0273			0.0273											
Failed Equipment																	
kg	40.27	--	40.27 .	--	40.27	--	--	--	40.27	--					--		
m^3	0.0584																
55-gal drum	0.0633		0.0633		0.0633												
600-gal can	0.0307		0.0307		0.0307												
Particulate Solids																	
kg	447.7	354.4	--	--	--	--	--	--	--	93.24					--		
m^3	0.624																
55-gal drum	2.970	2.690								0.280							
In-Process Material																	
kg	986.3	354.4	538.6	353.6	40.27	144.7		5.10	400.77		111.9	278.3			9.06		
m^3	2.810						0.0731										
55-gal drum	10.55	2.690							--			0.7441	0.110	3.324			
80-gal drum	0.943	--			--				--			--	--	--			
160-gal can	--	--			--				169.5			--	0.113	--			
600-gal can	0.2873	--							--			--	--	--			
HLW Glass																	
kg																182	277
m^3																	0.089
60-gal can																	0.4633

incineration/cementation facility nearly identical to that in WPF-3, and a new metals melting facility that essentially takes the place of the compaction facility that was present in WPF-2 and WPF-3. A schematic plan drawing of WPF-4 is contained in Figure 5.9. Shaded portions of the drawing indicate the portions of the building that are the same size as in WPF-1. More details on this facility are given in Appendix B.

5.4.2.1 Waste Metals Melting Facility

The design of this portion of the WPF follows the general concept used in the other parts of this facility and includes facilities for receiving and shipping process materials, facilities and equipment for transferring materials to other processes as required, hot cells with support services and galleries for operation and maintenance of equipment, and facilities for associated activities that are not required to be done remotely. The facility will be constructed of normal density concrete. Hot cell walls will be between 3- to 4-ft thick. The first floor of the facility will be underground, and all external walls will be sized to support soil loadings.

The furnace selected for this operation is a bottom-pour stationary crucible vacuum coreless induction melting furnace. This furnace is the one rated the best in a review and evaluation of metallic TRUW consolidation methods (Montgomery and Nesbitt 1983).

Most of these metallic waste pieces are small enough to be fed directly to the melter. Necessary size reduction of the few larger pieces will be done in existing cells. It may also be possible to avoid size reduction by simply encapsulating large metal objects within molten metals from the hulls and other small size metal wastes.

The vacuum coreless induction melting process involves the batch-wise introduction of metallic waste into an induction furnace. The waste must consist of elements smaller than 6 in. x 6 in. x 6 in. The waste is placed in a graphite crucible through an air lock feeder system. The crucible is heated by induction coils until the charge is melted. The melt is poured into repository canisters. Off gas from the melter is treated by scrubbing and filtration and passed through a ruthenium adsorber before it is released to the atmosphere.

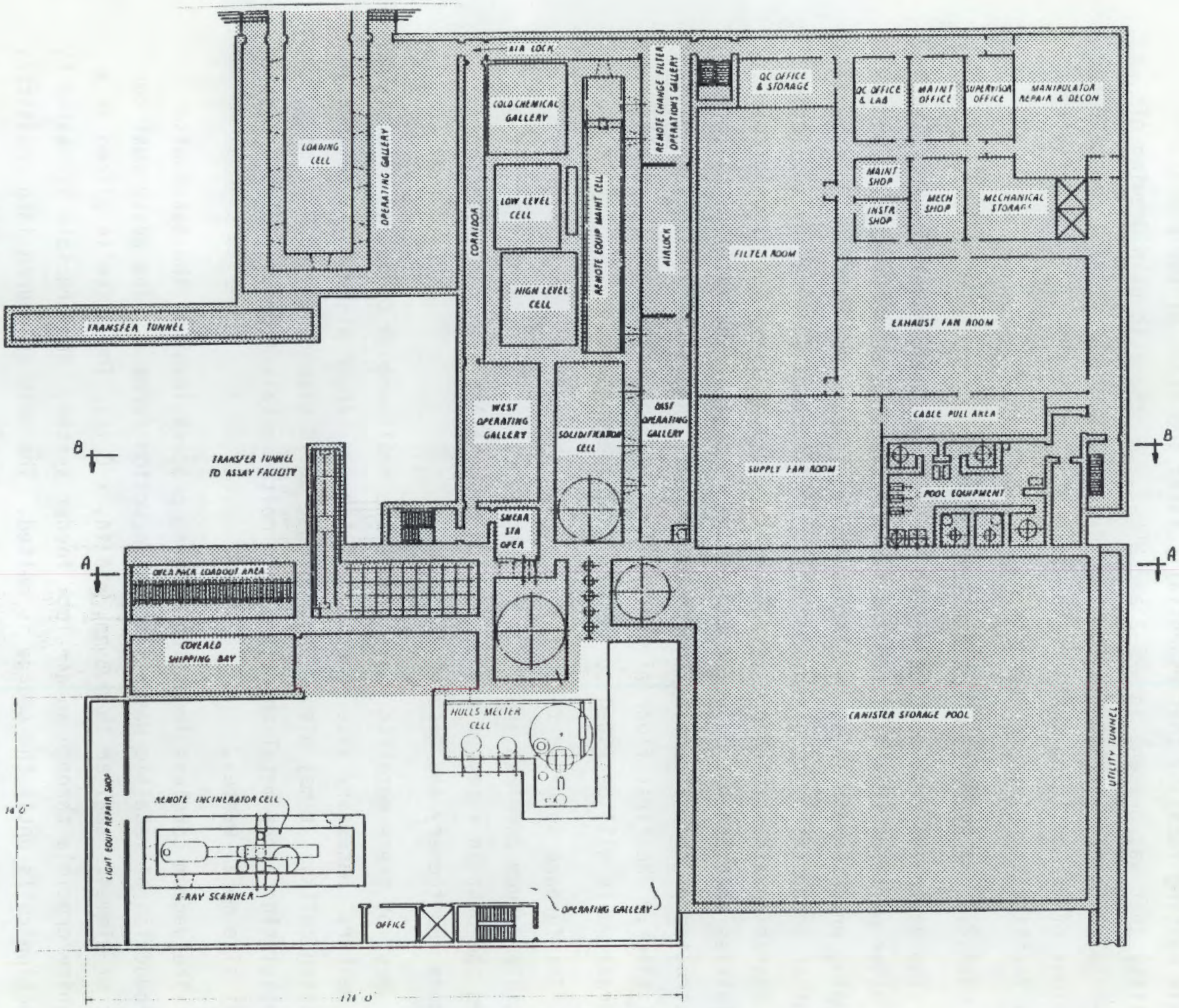

FIGURE 5.9. Plan View of WPF-4

5.4.3 Technology Assessment and R&D Needs for Metals Melting

The melting system must be able to operate in a contained atmosphere and use a crucible material suitable for melting zirconium. The inductoslag, rotating nonconsumable electrode, plasma arc, electroslag and vacuum coreless induction melting processes meet these criteria. These processes were all evaluated in a comparative study (Montgomery and Nesbitt 1983). The vacuum coreless induction melting process was selected as the most appropriate means to melt the metallic wastes that will be treated in the WPF.

The vacuum coreless induction melting process has not been used to melt the specific metallic waste constituents that will be treated in the WPF. The coreless induction melting process was used to melt waste products that simulate the TRU wastes present at the INEL (Tenaglia and McCall 1983). These wastes include carbon steel, stainless steel, chemical sludges, glass, polyethylene, and PVC. The process was considered feasible for processing INEL waste if problems of slag fluidity and crucible attack could be overcome. These problems should be much less severe in the alternative considered here because of differences in wastes fed to the melter and in the selection of crucible material.

Further development will be required before the melter could be operated in a remote environment. This development activity would investigate the capability of melting a variety of mixtures of metals, evaluate alternative off-gas collection systems, develop remote furnace feed, discharge and control capabilities, determine the life of graphite crucible materials, and demonstrate that process components could operate safely in a remote environment. These developments could be completed in 24 to 36 months (Montgomery and Nesbitt 1983).

The means necessary to reduce the size of failed equipment to the required size (less than 6 in. x 6 in. x 6 in.) will depend on the particular items of failed equipment present in the waste. Available shredders can reduce the size of metal bars, pipe, and sheet metal (Darnell and Aldrich 1983). Larger items of failed equipment (pumps, process equipment) may have to be disassembled by hand. Disassembly procedures have been developed to dismantle glove boxes and other waste products prior to decontamination (Allen 1982). These procedures should be applicable. They will have to be demonstrated on the failed equipment entering the WPF.

The segregation by size of incinerated, simulated TRU waste has been evaluated (Pattengill 1983). A trommel drum or a vibratory screen were recommended as devices that would effectively segregate ash aggregates larger than 1/4 in. from smaller ash fragments. The segregation of metallic residue from nonmetallic ash may require X-ray, magnetic, or other segregation devices in addition to trommel drums or vibratory screens.

5.5 METALS DECONTAMINATION PLUS INCINERATION/VITRIFICATION ALTERNATIVE 5

In this alternative waste treatment case, most of the metallic wastes are decontaminated so that they can be disposed of as LLW rather than TRUW. The materials removed from the surfaces during these operations are converted to oxides and immobilized in glass. As in the preceding case, combustible wastes are incinerated and the nonmetallic solid incinerator residues are also immobilized in glass.

5.5.1 Process Description for the Metals Decontamination Plus Incineration/Vitrification Alternative

Figure 5.10 identifies the process flow stream, and Table 5.5 identifies the quantities present in the different streams.

The hulls decontamination process involves removal of the contaminated surface by abrading with alumina or other fuel hulls in a device called a centrifugal barrel. Prior to this operation, the hulls are size reduced by crushing after cooling to the temperature of liquid nitrogen to make them brittle. Most of the other metallic wastes are decontaminated by vibratory finishing. Metals that are not decontaminated are those that are judged to be difficult or impossible to decontaminate. This might include things such as some pieces of failed equipment and the shredded metals that had passed through the incinerator. These metals are cemented in option (a) of this alternative and are melted in option (b).

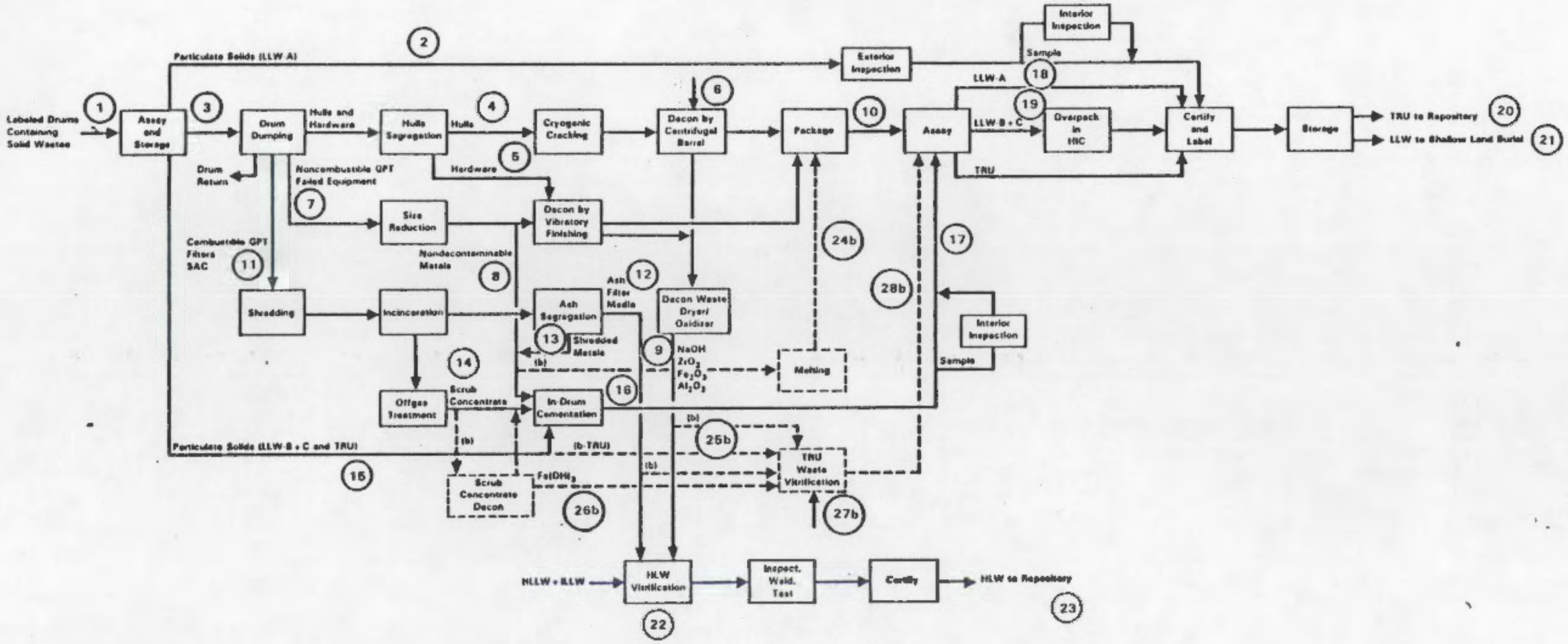

FIGURE 5.10. Alternative 5 Flowsheet-Metals Decontamination Plus Incineration/Vitrification

TABLE 5.5. Types and Quantities of Wastes in Each Process Stream--Alternative 5

Waste Type and Quantity (per MTU)	Waste Input 1	PWOT Waste 2	Decon or Incineration Feed 3	Hulls 4	Hardware 5	Abrasive (Al_2O_3) 6	Size Reduction Feed 7	Nondecontaminable Metals 8	Decon Waste 9	Metallic Wastes 10	Metallic Wastes 10b	Shredder Feed 11	Ash and Filter Media 12	Shredded Metals 13	Offgas Scrub Concentrate 14	Particulate Solids to Cement 15	Cement 16	Cemented Wastes 17a	Cemented Wastes 17b	LLW-A 18a	LLW-A 18b	LLW-BAC 19a	LLW-BAC 19b	TRUW 20a	TRUW 20b	LLW 21a	LLW 21b	Glass-Forming Oxides 22a	Glass-Forming Oxides 22b	Vitrified HLW 23a	Vitrified HLW 23b	Melted TRUW 24b	Particulate Solids (TRUW) 25b	$Fe(OH)_3$ Scavenger 26b	Glass-Forming Oxides 27b	TRUW Glass 28b
Hulls and Hardware																																				
kg	324.0	--	324.0	267.6	56.4	--	--	--	--	305.2	305.2	--	--	--	--	--	--																			
m^3	0.425																																			
160-gal can	--		--							0.4377	0.4377																									
600-gal can	0.200		0.200							--	--																									
Filters																																				
kg	15.11	--	15.11	--	--	--	--	--	--	--	4.24	15.11	5.213	4.24	--	--	--																			
m^3	0.1086																																			
55-gal drum	0.0400		0.0400																																	
80-gal drum	0.9433		0.9433																																	
600-gal can	0.0293		0.0293																																	
GPT																																				
kg	157.1	--	157.1	--	--	--	29.65	8.90	--	20.7	29.65	127.4	3.809	--		--	--																			
m^3	1.568														0.0724																					
55-gal drum	7.480		7.480							0.997																										
SAC																																				
kg	2.16	--	2.16	--	--	--	--	--	--	--	0.863	2.16	0.039	0.863		--	--																			
m^3	0.0207														0.00074																					
600-gal can	0.0273		0.0273																																	
Failed Equipment																																				
kg	40.27	--	40.27	--	--	--	40.27	12.1	--	29.1	40.27	--	--	--	--	--	--																			
m^3	0.0584																																			
55-gal drum	0.0633		0.0633							0.210																										
600-gal can	0.0307		0.0307																																	
Particulate Solids																																				
kg	447.7	354.4	--	--	--	--	--	--	--	--	--	--	--	--	--	93.24	--																			
m^3	0.624																																			
55-gal drum	2.970	2.690														0.280																				
In-Process Material																																				
kg	986.3	354.4	539.6	267.5	56.4	2.41	69.9	21.0	28.3	354.0	380.2	144.7	9.06	5.10		93.2	118																20.65	0.0006	143	201
m^3	2.810														0.0731			0.886	0.692	3.892	3.962	0.516	0.516	0.264	0.264	4.408	4.478									0.067
55-gal drum	10.55	2.690								1.207	1.207							--	--	--	--	--	--	--	--	--	--									--
80-gal drum	0.943	--								--	--							--	--	--	--	0.438	0.438	--	0.127	0.438	0.438					0.0038				--
160-gal can	--	--								0.4377	0.4475							--	--	--	--	--	--	--	--	--	--									0.123
600-gal can	0.2873	--								--	--																									--
HLW Glass																																				
kg																												289	191	413	277					
m^3																														0.135	0.089					
60-gal can																														0.765	0.4633					

The materials removed during decontamination are converted to oxides, as required, and are then immobilized in glass along with the alumina abrasive. Two options were considered here; in Alternative 5a these materials are immobilized in the HLW glass (which results in a significant increase in the quantity of this stream) and in Alternative 5b they are immobilized in a separate TRUW glass stream. In Alternative 5b, the fluorinator solids that are TRUW are also incorporated in the TRUW glass; these solids are cemented in Alternative 5a.

The shredding and incineration of the combustible wastes proceeds as in the previous two alternatives. In Alternative 5a the incinerator ash and filter media are immobilized with the HLW, as in the previous alternative, and in Alternative 5b they are immobilized with the secondary wastes from the decontamination processes and the TRUW fluorinator solids in the TRUW glass.

The off-gas scrub solution concentrate is cemented. In Alternative 5b, that portion of the cement that is TRUW is first decontaminated by scavenging with ferric hydroxide, so that all of the stream is then LLW. Thus, all of the cemented products in Alternative 5b will be LLW and none will be sent to geologic disposal.

5.5.2 Facility Description for the Metals Decontamination Plus Incineration/Vitrification Alternative

Although processes were selected and waste quantities were estimated for two options within this alternative, facility design was developed for only Alternative 5a discussed in Section 5.5.1. Therefore, the waste processing facility for this case, WPF-5, contains the metals decontamination facilities in addition to WAIC and HLW vitrification facilities as in the previous four cases, and an incineration/cementation facility identical to that in WPF-4. It does not contain a metals melter or a TRUW vitrification facility as discussed in Section 5.5.1 for Alternative 5b.

The HLW vitrification facility in WPF-5 is maintained essentially the same as that in WPF-4 even though the volume of HLW glass to be produced in WPF-5 is much larger because of the incorporation of the secondary wastes from the decontamination processes in this waste stream. This simplifying assumption for this preliminary evaluation is possible because the facility in WPF-4 contained two identical 100 percent capacity lines to assure that continuous operation would not be interrupted. Thus, HLW vitrification in WPF-5 does not have the redundant capacity that exists in the other WPFs.

A schematic plan drawing of WPF-5 is shown in Figure 5.11. Shaded portions of the drawing indicate the portions of the building that are the same size as WPF-1. More details on this facility are given in Appendix B.

5.5.2.1 Hulls Decontamination Facility and Equipment

The design of this portion of the WPF follows the general concept used in the other parts of this facility; i.e., facilities for receiving and shipping process materials and allowance for transferring materials to other processes as required, hot cells with support services and galleries for operation and maintenance of equipment and areas for associated activities that are not required to be done remotely. The facility will be constructed of normal density concrete. Hot-cell walls will be 3- to 4-ft thick. The first floor of the facility will be underground and all external walls will be sized to support soil loadings.

The decontamination process has four principal steps: 1) chilling of the hulls to below the alloy embrittlement temperature (by using liquid nitrogen), 2) fracturing the hulls into small pieces (a 2:1 to 6:1 size reduction) to expose the inner surfaces for effective cleaning, 3) cleaning the hulls in a centrifugal barrel machine using aluminum oxide grinding media to remove hull surface contamination, and 4) deactivating Zircaloy fines brought in with the contaminated hulls or produced by grinding the hulls.

Hulls are placed into a feed bin above a grizzly (a coarse size separation device having bars spaced over 1 in. apart) and a screen which separates oversize fuel assembly end pieces and Zircaloy fines from sectioned hulls. Following separation, the hulls are automatically fed into the rotary chiller (about 24 in. diameter, 10 ft long) and are propelled through the chiller by an auger that tumbles the hulls through the refrigerant. The cryogenically chilled hulls are cracked into separate pieces in a roll mill adjusted to prevent excessive size reduction. The roll mill has two counter-rotating rolls about

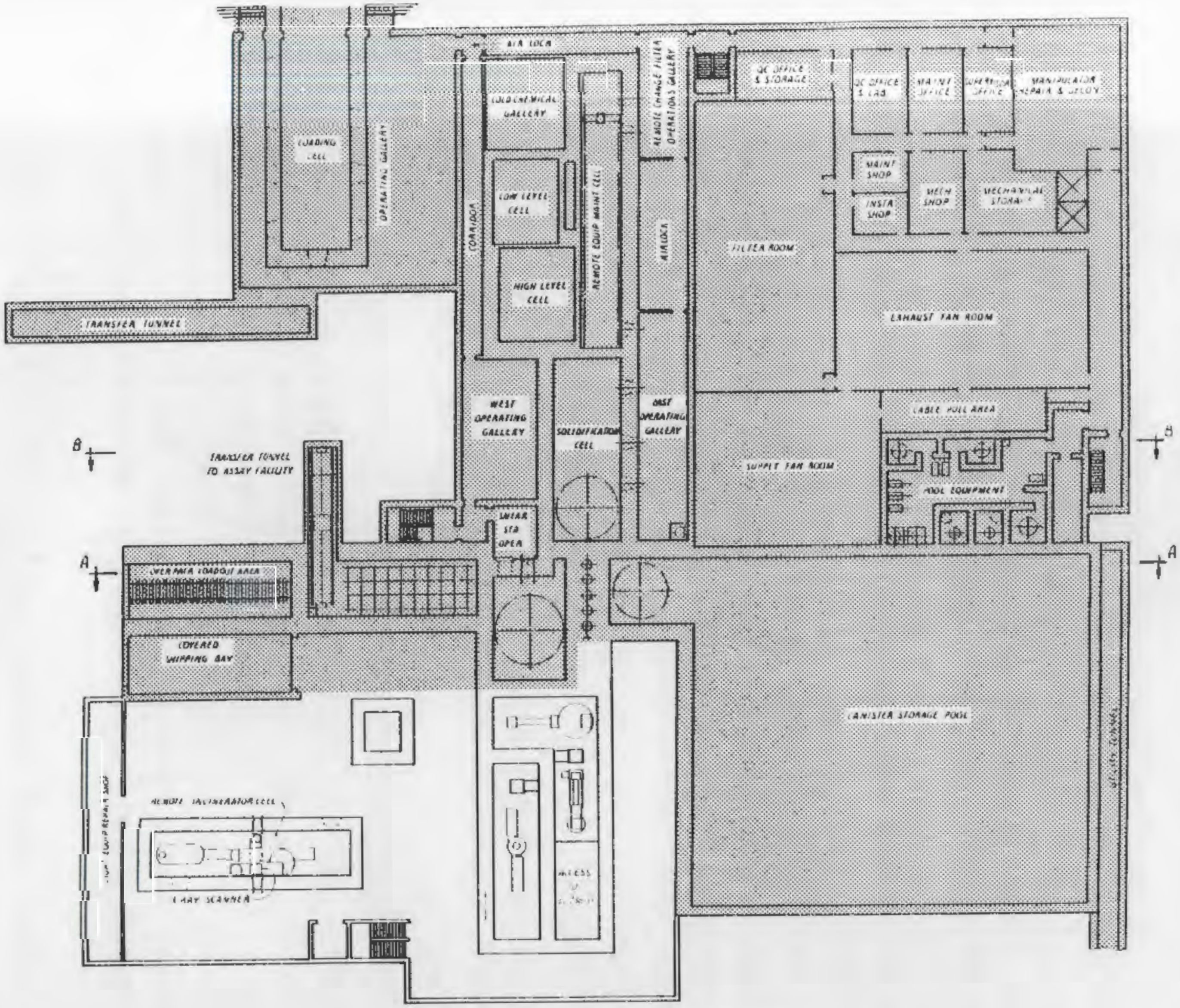

FIGURE 5.11. Plan View of WPF-5

9 in. diameter and 6 in. wide. After being cracked and warmed, the hulls are transported to the centrifugal barrel machine.

The centrifugal barrel machine has two drums, together capable of handling about 12 ft^3 of hulls and aluminum oxide grinding media, mounted opposite each other on the edge of a rotatable turret. These are in a stationary housing. The turret is rotated in one direction about its axis, the drums in the counter direction. The turret rotation creates a controlled centrifugal force within the drums, pressing hull pieces and aluminum oxide together. The opposed drum rotation provides a smooth sliding action between the materials to remove contaminated surface to a controlled depth. Normal process cycles for most industrial deburring applications are less than half an hour; hulls decontamination times are anticipated to be about the same.

Following decontamination, the hull pieces are rinsed and screened free of grinding media, hull fines, and surface contaminants, and then are dried, packaged, assayed, and disposed of as LLW. The mixture of grinding media and hull fines is dried and deactivated in a dryer/oxidizer unit and is then transferred to the vitrification facility to be incorporated in the HLW glass.

Oversize fuel assembly hardware is collected and decontaminated by vibratory finishing in the other metallic waste decontamination facility (Section 5.5.2.2).

5.5.2.2 Failed Equipment and Other Metallic Wastes Decontamination

A facility employing vibratory finishing is used to decontaminate failed process equipment and other metal wastes from TRU waste to LLW or from one LLW classification to a less restrictive classification. The approach taken in this concept is to process both contact and remote-handled wastes separately but in the same facilities on a campaign bases. The design of this facility follows the general design concepts described earlier for other portions of the WPF.

A preliminary decontamination is performed in a glove-box type enclosure using water spray equipment or other cleaning devices to remove loosely adhered surface contaminants from the waste metal materials. Following the preliminary decontamination, the contaminated metal is disassembled and sectioned as necessary to fit within the vibratory finisher. Sectioning is done in a second glove-box type enclosure equipped with oxygen/acetylene cutting torches, plasma arc cutting torches, mechanical cutting saws, or other cutting devices.

The vibratory finishing process, adapted from a process used in the metal finishing industry for deburring metal parts, combines mechanical scrubbing and chemical action to remove the tightly adhered contaminants from surfaces of the sectioned metal parts. Processing occurs in a 5.25-ft diameter, 12 ft^3 vibrating, annular tub that contains hardened metal-grinding media of various shapes. The shape variations permit the media to enter corners and crevices of the waste. A chemical solution, which both loosens and rinses contaminants from surfaces of the waste, is recirculated between a collection tank and the vibrating tub.

5.5.3 Technology Assessment and R&D Needs for Metals Decontamination

The vibratory finishing process has been used commercially since 1957 to improve surface finishes and clean metallic and nonmetallic objects. Large objects must be sectioned before they are placed in the vibratory tub. A sectioning to a 6 in. dimension is typical. Mechanical cutting methods have been used on a wide variety of radiologically contaminated materials (McCoy et al. 1982a). A pilot scale sectioning-vibratory finishing demonstration program has been conducted (McCoy et al. 1982b). The program demonstrated the ability of the sectioning-vibratory finishing process to decontaminate beta/gamma and TRU contaminated metallic and nonmetallic objects of various shapes and sizes. However, the operation of the disassembly and vibratory finishing processes in a remote environment has not been demonstrated.

Neither the centrifugal barrel machine to abrade surface contamination from the fuel hulls nor the chiller and crusher used to expose interior surfaces has been adapted to process fuel hulls in a remote environment. Nonradioactive proof of principal tests of these components have been performed at PNL. Determination of the degree of decontamination achievable awaits work with irradiated fuel hulls.

6.0 DESCRIPTION OF TREATED WASTES

This section provides summary comparisons of the quantities and properties of the treated wastes resulting from the treatment alternatives described in this report. Additional data are contained in Appendix C.

6.1 TREATED WASTE QUANTITIES

Table 6.1 compares the total number of the various sized containers required to dispose of the reprocessing wastes for each of the treatment alternatives examined in this study. The quantities are summarized according to the three major categories of waste: LLW, TRUW, and HLW. This table also compares the total waste volumes in each category for each treatment alternative.

A more detailed comparison of the waste quantities is presented in Table 6.2, where breakdowns by LLW and TRUW classification are included. The waste quantities are also separated according to the type of treatment in this table. Even more detailed breakdowns are presented for each of the treatment alternatives in Appendix C (Tables C.1 through C.6).

Radionuclide contents of TRUW resulting from the various treatment alternatives are compared in Table 6.3 according to type of treated waste (waste form). This comparison is made for a typical fission product, Cs-137 and a typical transuranic, Pu-238; somewhat different results will prevail for some other radionuclides (see Appendix A, Table A.7), but these data provide a good comparison of the division of radionuclides among various waste forms for the treatment alternatives examined.

6.2 PROPERTIES OF TREATED TRUW

In addition to comparing the quantities of treated wastes, as in Section 6.1, it is also important to compare the properties of the wastes resulting from the various treatment alternatives examined in this study. Because of insufficient data, quantitative comparisons cannot be made, but some qualitative comparisons are possible.

TABLE 6.1. Waste Containers from Treatment Alternatives, by Waste Category

Treatment Alternative	Treatment Description	Waste Category	Containers/1500 MTU					Waste Container Internal Volume, m^3/1500 MTU	Containers Volume Relative to That in Alternative 1
			55-gal	80-gal	160-gal	600-gal	60-gal		
1	Package Without	LLW	14,879	169	--	42	--	3,244	1.00
	Treatment Plus	TRUW	951	1,247	--	389	--	1,459	1.00
	HLW Vitrification	HLW	--	--	--	--	695	158	1.00
			15,830	1,416	--	431	695	4,860	
2	Compaction Plus	LLW	4,387	--	1,287	38	--	1,779	0.55
	HLW Vitrification	TRUW	163	--	527	8	--	371	0.25
		HLW	--	--	--	--	695	158	1.00
			4,550	--	1,814	46	695	2,308	
3	Incineration/Cementation	LLW	4,858	--	456	38	--	1,374	0.42
	Plus Compaction Plus	TRUW	484	--	386	8	--	353	0.24
	HLW Vitrification	HLW	--	--	--	--	695	158	1.00
			5,342	--	842	46	695	1,885	
4	Metals Melting Plus	LLW	4,985	--	--	--	--	1,038	0.32
	Incineration/HLW	TRUW	166	--	170	--	--	138	0.09
	Vitrification	HLW	--	--	--	--	695	158	1.00
			5,151	--	170	--	695	1,334	
5a	Metals Decontamination	LLW	6,612	--	657	--	--	1,774	0.55
	Plus Incineration/HLW	TRUW	396	--	--	--	--	82	0.06
	Vitrification	HLW	--	--	--	--	1,057	240	1.52
			7,008	--	657	--	1,057	2,096	
5b	Metals Decontamination	LLW	6,716	--	657	--	--	1,796	0.55
	Plus Incineration/TRUW	TRUW	--	--	190	--	--	115	0.08
	Vitrification	HLW	--	--	--	--	695	158	1.00
			6,716	--	847	--	695	2,069	

TABLE 6.2. Waste Containers from Treatment Alternatives, by Waste Form and Waste Classification

Treatment Alternative	Treatment Description	Waste Form	Container Size, Gal	Containers/1500 MTU								
				LLW				TRUW				
				A	B	C	Total	CH	RH	Total	HLW	Grand Total
1	Package Without Treatment Plus HLW Vitrification	Untreated	55	13,318	17	1,544	14,879	660	291	951	--	15,830
			80	86	20	63	169	1,114	133	1,247	--	1,416
			600	19	6	17	42	4	385	389	--	431
		HLW Glass	60	--	--	--	--	--	--	--	695	695
							15,090			2,587		18,372
2	Compaction Plus HLW Vitrification	Untreated	55	4,043	17	327	4,387	70	93	163	--	4,550
			600	19	6	13	38	4	4	8	--	46
		Compacted	160	1,138	1	148	1,287	63	464	527	--	1,814
		HLW Glass	60	--	--	--	--	--	--	--	695	695
							5,712			698		7,105
3	Incineration/ Cementation Plus Compaction Plus HLW Vitrification	Untreated	55	4,043	17	--	4,060	70	--	70	--	4,130
			600	19	6	13	38	4	4	8	--	46
		Compacted	160	402	--	54	456	16	370	386	--	842
		Cemented	55	216	--	582	798	15	399	414	--	1,212
		HLW Glass	60	--	--	--	--	--	--	--	695	695
							5,352			879		6,925
4	Metals Melting Plus Incineration/HLW Vitrification	Untreated	55	4,035	--	--	4,035	--	--	--	--	4,035
		Melted	160	--	--	--	--	--	170	170	--	170
		Cemented	55	368	--	582	950	--	166	166	--	1,116
		HLW Glass	60	--	--	--	--	--	--	--	695	695
							4,985			336		6,016
5a	Metals Decontamination Plus Incineration/HLW Vitrification	Untreated	55	4,035	--	--	4,035	--	--	--	--	4,035
		Decontaminated	55	1,643	--	--	1,643	--	--	--	--	1,643
			160	--	--	657	657	--	--	--	--	657
		Cemented	55	160	25	749	934	178	218	396	--	1,330
		HLW Glass	60	--	--	--	--	--	--	--	1,057	1,057
							7,269			396		8,722
5b	Metals Decontamination Plus Incineration/TRUW Vitrification	Untreated	55	4,035	--	--	4,035	--	--	--	--	4,035
		Decontaminated	55	1,643	--	--	1,643	--	--	--	--	1,643
			160	--	--	657	657	--	--	--	--	657
		Cemented	55	264	25	749	1,038	--	--	--	--	1,038
		Melted	160	--	--	--	--	--	6	6	--	6
		TRUW Glass	160	--	--	--	--	--	184	184	--	184
		HLW Glass	60	--	--	--	--	--	--	--	695	695
							7,373			190		8,258

TABLE 6.3. Comparison of TRUW Radionuclide Distributions Among Treated Waste Forms

Treatment Alternative	Treatment Description	Waste Form	Distribution of TRUW Radionuclides Among Waste Forms, %[(a)] 137-Cs	238-Pu
1	Package Without Treatment Plus HLW Vitrification	Untreated	100	100
		HLW Glass	--	--
2	Compaction Plus HLW Vitrification	Untreated	0.05	7.7
		Compacted	100	92.3
		HLW Glass	--	--
3	Incineration/Cementation Plus Compaction Plus HLW Vitrification	Untreated	0.04	7.7
		Compacted	94.1	56.6
		Cemented	5.8	35.7
		HLW Glass	--	--
4	Metals Melting Plus Incineration/HLW Vitrification	Melted	96.0	73.2
		Cemented	0.01	0.04
		HLW Glass	4.0	26.8
5a	Metals Decontamination Plus Incineration/HLW Vitrification	Cemented	1.9	11.8
		HLW Glass	98.1	88.2
5b	Metals Decontamination Plus Incineration/TRUW Vitrification	Melted	1.9	11.7
		TRUW Glass	98.1	88.3
		HLW Glass	--	--

(a) Total quantities in initial TRUW are given in Table A.6.

There are many criteria that will likely have to be met by the treated TRUW before it can be disposed of in a geologic repository. Such criteria have not yet been defined. One purpose of this study was to assist in the definition of reasonable criteria by establishing the costs of their implementation. Thus, the wastes resulting from some of these treatment alternatives will likely not meet the criteria that are eventually established.

Among the waste form characteristics that are likely to be covered by waste disposal criteria, and that can be controlled by waste treatment processes, are:

- presence of combustible material
- gas generation possibility
- presence of particulate material
- presence of free liquids
- presence of pyrophoric material
- release rate of radionuclides.

A summary comparison, based on these criteria, of the treatment alternatives is given in Table 6.4. Brief discussions of these comparisons follow.

Combustible Material

Combustible materials are present in the wastes from treatment Alternatives 1 and 2, but not in the wastes from Alternatives 3, 4, and 5. The fire hazard in the waste from Alternative 2 should be lower than in the waste from Alternative 1 because of the compactions that occur in Alternative 2.

Gas Generation

Gases can be generated by microbial actions on or chemical decomposition of organic materials, and by radiolytic decomposition of organic materials or water. The mechanisms involving organic materials would be operative, and probably about equal in result, in Alternatives 1 and 2, but not in Alternatives 3, 4, and 5. Radiolyses of water would not be important in Alternatives 1 and 2, but could be in Alternatives 3, 4, and 5a where some of the wastes are cemented. In these three alternatives, radiolyses of water would generate the most gas in Alternative 3 and the least gas in Alternative 4, because of the relative amounts of radionuclides present in the cemented waste forms (see Table 6.3).

Particulate Material

Particulate materials will be present in the largest quantities in Alternatives 1 and 2, where the fluorinator solids are disposed of without

TABLE 6.4. Comparison of TRUW Properties in the Treatment Alternatives

Treatment Alternative	Combustible Material Present	Gas Generation Possibility	Particulate Material Present	Free Liquid Present	Pyrophoric Material Present	Radionuclide Release Probability[a]
1	Yes	Yes	Yes	No	Maybe	Highest
2	Yes	Yes	Yes	No	Maybe	High
3	No	Yes	No	No	Maybe	High
4	No	Slight	No	No	No	Low
5a	No	Yes	No	No	No	Low
4b	No	No	No	No	No	Low

(a) Release to water within the repository.

treatment. However, these wastes have a low radionuclide content (see Table A.8) so this problem may not be severe. Another possible source of particulate material is the cladding hulls, where fines may be present initially and may be formed during compaction in Alternatives 2 and 3. However, it is not known if compaction results in larger or smaller quantities of loose particulate material.

Free Liquids

No free liquid is anticipated in any of the treated wastes. Careful control of the cementation processes in Alternatives 3, 4, and 5a will be required to assure the absence of free liquid in the cemented products.

Pyrophoric Material

Cladding hull fines can be pyrophoric under certain conditions. Such fines may be present in Alternative 1, and additional fines may be formed during compaction in Alternatives 2 and 3; however, it is not known if compactions results in larger or smaller quantities of loose particulate material. No pyrophoric material should be present in the treated TRUW from Alternatives 4 and 5.

Radionuclide Release Probability

In this comparison of alternative waste forms, the release of radionuclides from the waste itself into the groundwater that might enter a geologic repository is of primary concern. This release to the groundwater does not necessarily mean that the radionuclides are released from the repository, since the movement of many radionuclides may be greatly retarded by precipitation and/or sorption reactions as the water passes through the soil. Thus, the release from the repository of many important radionuclides may be insensitive to waste form. However, more stable waste forms do provide containment of highly mobile radionuclides and also provide an added safety factor for those that are retarded by precipitation and/or sorption reactions. The discussion in this section is limited to possible releases from the waste to the repository groundwater. Release from the repository itself is covered in Section 7.1.

With untreated wastes, as in treatment Alternative 1, the contained radionuclides must be assumed to be 100 percent available for dissolution into the groundwater as soon as the containers fail. Some decrease in the rate of dissolution of at least some radionuclides may result in Alternative 2, because of compaction of much of the waste, but this decrease may not be very large. Alternative 3 provides an additional improvement by immobilizing part of the waste in cement; however, this improvement is not great because over 50 percent of the radionuclide content remains with untreated or compacted wastes (Table 6.3). A great improvement in waste form stability occurs in Alternatives 4 and 5b, where greater than 99.9 percent of the radionuclide content is present in metal or glass monoliths. Alternative 5a should also provide low radionuclide releases even though larger fractions of radionuclides are immobilized by cementation than in Alternative 4. About 125 percent of the Pu is cemented in Alternative 5a (Table 6.3), but Pu release from cemented waste forms is very low (Ross 1982). Only about 2 percent of the fission products are cemented in Alternative 5a.

7.0 PERFORMANCE ASSESSMENT

This section describes an assessment of the performance of the TRU waste forms. Both near-term and long-term performance of the waste forms were evaluated. Near-term performance was measured in terms of the radiation exposures and potential accident risks that result from processing the TRU waste streams and transporting the TRU wastes to the repository for disposal. Long-term waste form performance was measured in terms of the radionuclide release rate from the repository. For the latter, the SCOPE computer code was used to model the releases from the TRU waste packages under representative groundwater conditions. It should be recognized that the near-term and long-term performance assessments performed in this study were undertaken to develop any initial idea about the scope of waste performances. More detailed data and analyses are needed to establish the absolute performance of the different waste forms. Differences in performance under representative groundwater conditions cannot be interpreted as absolute differences in the relative performance of the actual repository sites. They provide a preliminary indication of potential differences that require more detailed evaluation.

7.1 LONG-TERM REPOSITORY PERFORMANCE ASSESSMENT

Treatment of TRU wastes could be of benefit when release of radionuclides from a repository is considered. In general, treated waste forms are more chemically stable and physically durable than untreated wastes. This section describes a performance assessment undertaken to evaluate release patterns of radionuclides from various TRU waste forms when they are transported from a repository to the environment. The relative benefits of treating the wastes are measured in terms of the EPA regulations on HLW disposal (40 CFR 191). However, since this report presents a scoping assessment and because important site-specific data remain to be collected in the future, results cannot be used to compare the performance of specific sites to each other or to the EPA criteria.

Four types of geologic media are currently under consideration as potential locations for a repository. These four media are basalt, salt, tuff, and granite. Since research into the characteristics of these media is on-going, the crucial parameters which define the repository environment are not completely characterized. These environmental parameters are the subject of research being conducted by DOE. Accordingly, the analyses discussed in this section are generic in nature and use best-estimate or representative parameter values where needed to define the waste disposal environment. Although the values are preliminary, they are adequate for comparing the relative performance of the various TRU waste forms. Use of the results for comparison of the disposal media, however, is an inappropriate application.

Five TRU waste treatment alternatives (see Table 4.1) were examined in this study. These are:

1. package without treatment (serves as the base-case for comparison purposes)

2. compaction of compactible wastes and package the remaining wastes without treatment

3. incineration of combustible wastes (plus subsequent incorporation of ash in cement), compaction of remaining wastes that are compactable, and package all other wastes without treatment

4. melting of metallic wastes, incineration of combustible wastes (plus subsequent incorporation of ash into a glass waste form)

5. decontamination of metallic wastes to result in their classification as LLW, incineration of combustible wastes and subsequent incorporation into glass, plus cementing of fluorinator solids and metallic wastes that cannot be decontaminated

These five waste treatment alternatives will produce five different TRU waste forms: 1) untreated; 2) compacted; 3) cemented; 4) melted metals and

5) vitrified wastes. The waste treatment alternatives are based on treatment of wastes from a reprocessing plant; however, the relative performance of the waste forms in the repository environments is believed to also be applicable to TRU wastes generated without fuel reprocessing.

7.1.1 Method for Determining the Relative Performance of TRU Waste Forms

This section briefly describes SCOPE, the simplified radionuclide transport simulator that was used in this assessment. SCOPE (Version 1.0) which is described in detail by Petrie et al. (1983), is an acronym for Simplified Codes for Performance Evaluation of radionuclide transport. SCOPE is comprised of complex "bookkeeping" codes that track the transport and uptake of radio-nuclides as they move through the repository system and into the accessible environment. This computer code cannot replace the sophisticated, multi-dimensional analyses that will be required to generate information for use in licensing the repository; however, it suffices for performing relatively simple scoping calculations to be used for relative comparisons of alternatives.

The SCOPE system (Version 1.0) consists of three groups of computer programs (see Figure 7.1). The first group, the BAIRN system, is comprised of four subprograms (BAIRN 1 to BAIRN 4) that simulate transport of radionuclides in a groundwater system from the repository to the accessible environment. The EXPOSE program is the second group. EXPOSE uses the results from BAIRN to calculate the integrated exposure to radionuclides in accordance with EPA repository release criteria (40 CFR 191). The third group consists of dose codes PABLM and ALLDOS. These codes use the output from BAIRN to estimate the radiation doses (and subsequent health effects) to the general public (Napier et al. 1980, Strenge et al. 1980). The SCOPE system also uses two CONVERT programs, CONBABLM and CONALDOS, which translate the information from BAIRN into a form that can be understood by the dose codes.

BAIRN uses analytical solutions to the equations for one-dimensional solute transport for up to a three-member radionuclide decay chain (Harada et al. 1980). Analytical solutions for single radionuclides are derived by BAIRN 1;

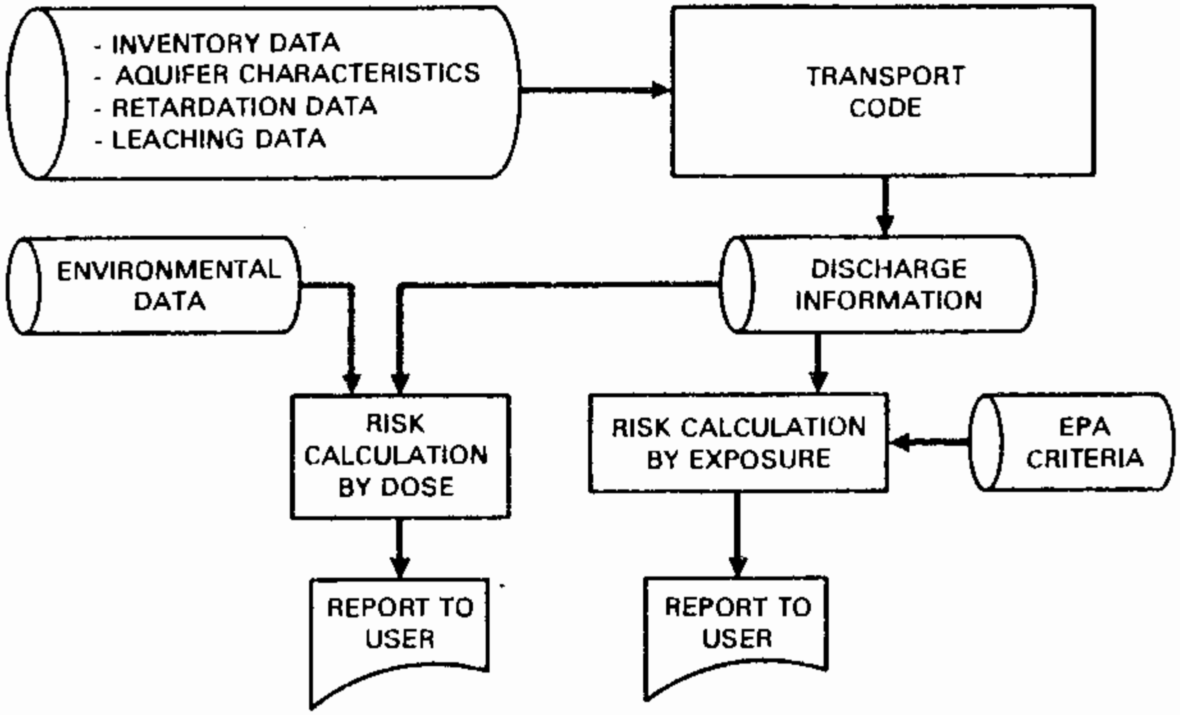

FIGURE 7.1. Generalized SCOPE System

two- and three member decay chains are simulated by BAIRN 2 and BAIRN 3, respectively. The equation used in the BAIRN series may be written as follows:

$$B_i \frac{\partial C_i}{\partial t} = D \frac{\partial^2 C_i}{\partial x^2} - V \frac{\partial C_i}{\partial x} - B_i \lambda_i C_i + B_{i-1} \lambda_{i-1} C_{i-1}$$

where c = concentration
b = retardation factor
d = dispersion coefficient
v = pore velocity
= radioactive decay constant

The subscripts in the equation refer to the position of the radionuclide in the decay chain. The principal simplifying assumptions for BAIRN's analytical solutions are:

- Sorption is in equilibrium and fully reversible.
- All elements are infinite soluble during transport; i.e., solubility limits were not included in the transport analysis (these were included in the source term calculations).
- Dispersion for all radionuclides is equivalent.
- Fluid flow is steady-state.
- Radioactivity is released into groundwater from the TRU waste as a band release.
- The flow path is uniform and one-dimensional.

BAIRN 4 simulates the transport of decay chains that are longer than three members and also prepares the data generated by BAIRN 1, BAIRN 2, and BAIRN 3 into a format that is understandable to the subsequent codes. BAIRN 4 approximates decay chains of four or more radionuclides by combining the results of 1-, 2-, and 3-member chain solutions of the above equation.

The EXPOSE program estimates the potential hazard to the public that may be caused by the transport of radionuclides from the disposal area to the boundary between the repository and the accessible environment. EXPOSE uses the results from BAIRN to calculate the amount of radioactive material passing through the boundary over time (i.e., radionuclide-specific release rates). The results are then compared with the allowable release criteria for each radionuclide given by the EPA's regulations (40 CFR 191).

The programs ALLDOS and PABLM, which calculate health effects, were not used in this assessment because EPA's regulations are given in terms of the maximum allowable radionuclide release rates. Therefore, for this preliminary analysis, it was not considered necessary to calculate the health effects that may result from potential releases.

7.1.2 Bases and Assumptions

The major bases and assumptions used to determine the relative performance of the various waste forms and the source-term release models for each waste type that drive the SCOPE program are described in this section. Each waste form has its own degradation and leaching characteristics, and the conceptual release models differ among waste forms. These conceptual release models are discussed below.

Waste container lifetime for all untreated and compacted waste forms is conservatively assumed to be zero. Water is assumed to flow through the waste with no impedance (i.e., unrestricted flow is assumed). The release of many radionuclides is assumed to be constrained by appropriate solubility limits. Elements that are not solubility-controlled are arbitrarily assumed to be released at a rate of 1 percent of the original amount per year. Solubilities depend on groundwater chemistry. For this study, two simple groundwater chemistry conditions were assumed--oxidizing and reducing. The effects of other water chemistry parameters, such as pH and anion concentrations, were not evaluated. The solubility values used in this assessment are shown in Table 7.1 (these values are derived in Appendix D). The recucing environment of pH 9 to

TABLE 7.1. Reference Solubility Values for Oxidizing and Reducing Groundwater Conditions, g/l

Element	pH 9-10 Reducing	pH 7, Oxidizing
Ni	3.3×10^{-7}	1.7×10^{-3}
Np	2.5×10^{-10}	5×10^{-3}
U	1.4×10^{-8}	2×10^{-3}
Pu	6×10^{-10}	5×10^{-5}
Th	4×10^{-7}	1×10^{-6}
Pa	2×10^{-7}	2×10^{-7}
Am	1×10^{-10}	1×10^{-9}
Cm	1×10^{-10}	1×10^{-9}
Zr	1×10^{-7}	1×10^{-7}
Sn	1×10^{-7}	1×10^{-7}
Sr	6×10^{-4}	essentially infinite
Ra	6×10^{-4}	essentially infinite
Pb	1×10^{-4}	essentially infinite
Se	1×10^{-6}	1×10^{-6}
Pd	2×10^{-8}	2×10^{-8}
Tc	1×10^{-12}	essentially infinite

10 is assumed to apply to basalt. The oxidizing environment of pH 7 is assumed to apply to tuff. For granite and salt, conditions are not well defined so both reducing and oxidizing conditions were considered.

Cemented, vitrified, and melted-metal waste forms were assumed to be impermeable to water flow. The dissolution rate of the waste matrix in the specified groundwater conditions was used to approximate the release rate of radionuclides from a waste form. Nonsolubility-controlled elements were assumed to be released from the waste form at this rate. Solubility-controlled elements were assumed to be released at the lesser of either the matrix dissolution rate or the rate governed by solubility controls. The UCB mass-transport model (Chambre et al. 1982) was used for solubility-controlled elements.

The release rate of the TRU inventory was determined by calculating the release rate (in units of elemental mass per year) from each waste container and summing over all waste types to obtain a total release rate. The release period (or duration of release) was assumed to be the amount of time over which the entire inventory would be released, assuming it was released at a constant rate. This assumption tends to underestimate the actual release period because it conservatively overestimates the average release rate. However, the assumption yields information that is adequate for comparison purposes.

For this assessment, radionuclides released from the waste forms were assumed to be transported to the assessable environment by groundwater transport. Radionuclide transport via groundwater is slowed by sorption to the repository media. The delay depends on the characteristics of the porous media and groundwater chemistry. Groundwater travel time was assumed to be 10,000 years. Radionuclide travel times are a function of the groundwater travel time, distribution (or sorption) coefficients (K_d), and the effective porosity of the repository medium. The distribution coefficients used in this assessment are shown in Table 7.2 for each possible repository medium. Groundwater transport in salt could occur in the sedimentary rock which borders most salt sites; groundwater flow in sedimentary media was assumed to be saturated.

TABLE 7.2. Reference Sorption Coefficients (K_ds) for Four Host Rock Types, ml/g

Element	Basalt	Granite	Tuff	Salt
H	0	0	0	0
C	0	0	0	0
Co	20	20	20	10
Ni	15	20	20	5
Se	20	3	5	5
Kr	0	0	0	0
Rb	50	25	100	50
Sr	100	10	250	50
Zr	30	30	30	50
Nb	30	30	30	50
Mo	5	2	1	0
Tc	50	20	1	0
Ru	5	5	3	10
Pd	5	5	10	50
Cd	20	20	20	10
Sn	20	20	20	10
Sb	5	3	3	0
I	0	0	0	0
Cs	500	150	500	100
Sm	20	20	500	50
Eu	20	20	500	50
Ho	20	20	500	50
Pb	20	20	300	50
Ra	50-100	100	300	20
Th	50	30	50	100
Pa	20	20	50	20
U	10	50	5	50
Np	100	100	5	50
Pu	100	100	100	100
Am	20	50	300	100
Cm	20	50	300	100
Cf	20	50	300	100
3 (g/ml)(a)	10.0	33.0	9.7	11.5

(a) Retardation factor = 1 + BK_d.

Travel distance is not a concern here because no comparisons are made among repository media and no judgements are made regarding the regulatory release criteria.

7.1.3 Results and Conclusions

Scoping calculations were first performed to determine which radionuclides dominate the repository release rate. It was found that C-14 and I-129 are most important for the first 10,000 years. In situations where oxidizing groundwaters exist, Tc-99 becomes an important contributor to the release rate for times approaching 100,000 years after repository closure. Since this assessment is primarily concerned with the first 10,000 years after repository closure, only C-14 and I-129 release rates are discussed. It is assumed that the inventories of C-14 and I-129 in the TRU wastes were constant for all treatment alternatives. However, it should be noted that essentially none of these radionuclides would remain in the incinerated, melted, or vitrified waste forms because they would vaporize at the required waste processing temperatures and would be released to the facility off-gas system. This phenomenon, which results from waste processing (i.e., removal of the most troublesome radionuclides from the waste form), was not explored further.

The results of this assessment for the five waste treatment alternatives are shown in Table 7.3. The results are not affected by the type of geologic medium. This relative insensitivity to type of repository medium is a result of the assumption that groundwater transport of C-14 and I-129 is not retarded by the geologic medium. Since retardation properties are determined by the specific medium, the performance of the geologic containment system will be independent of medium for those radionuclides that are not retarded. A sensitivity analysis that evaluates the effect of retardation is discussed subsequently.

No significant differences were found among the calculated release fractions for Alternatives 1, 2 and 3. Thus, from a repository performance standpoint, there appears to be no incentive to compact or incinerate the wastes

TABLE 7.3. Releases of I-129 and C-14 to the Accessible Environment, Fraction of Total Inventory[(a)]

Waste Treatment Alternative Number/Element	Fractional Release[(b)] Reducing Basalt	Reducing Granite and Salt	Oxidizing Granite and Salt	Oxidizing Tuff
1				
Carbon	0.0195	0.0195	0.0195	0.0195
Iodine	0.0004	0.0004	0.0004	0.0004
2				
Carbon	0.0195	0.0195	0.0195	0.0195
Iodine	0.0004	0.0004	0.0004	0.0004
3				
Carbon	0.0195	0.0195	0.0195	0.0195
Iodine	0.0004	0.0004	0.0004	0.0004
4				
Carbon	1×10^{-7}	1×10^{-7}	1×10^{-6}	1×10^{-7}
Iodine	1×10^{-9}	1×10^{-9}	1×10^{-8}	1×10^{-9}
5a				
Carbon	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
5b				
Carbon	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-7}

(a) Release fractions calculated for the first 10,000 years after repository closure.

(b) Given as fraction of release limits stated in 40 CFR 191.

(with subsequent incorporation of incinerator ash into cement). Waste treatment Alternative 4, which includes provisions for melting metallic wastes, has the lowest release fractions. This indicates that melting of metallic wastes is more favorable than compaction (i.e., melting is the primary difference between Alternatives 3 and 4). Alternatives 5a and 5b exhibit somewhat larger release fractions than Altenative 4. Therefore, there does not appear to be a repository-performance incentive for decontaminating the metallic wastes.

The primary reason that a consolidated metal waste form performs better than others is because the metal waste form is essentially impermeable to groundwater. The dissolution of the metal matrix occurs by a diffusion process (i.e., a concentration gradient is formed in the groundwater around the waste form). The radionuclide release rates from metal waste forms were based on their rate of dissolution in the specified groundwater conditions. As a result, the radionuclide concentration at the waste form/groundwater interface is at its solubility limit. Thus, since this is a diffusion process, there is no driving force for radionuclide release from the metal waste form at a rate higher than the dissolution rate of the metal. Therefore, the radionuclide dissolution rate is no higher than the metal matrix dissolution rate and, since the leach rates of the metallic elements are significantly lower than those for most radionuclide elements, a substantial benefit is calculated for this treatment alternative. In other words, waste form performance (and thus repository performance) will be improved if more metal is present in the waste forms. The TRU waste decomtamination alternatives (Alternatives 5a and 5b) actually reduce the amount of metal in the waste forms and, thus, downgrade the performance of the waste form in the repository.

As mentioned previously, the results in Table 7.3 were insensitive to the type of host rock because it was assumed that migration of C-14 and I-129 is not retarded by the geologic medium. Retardation, caused by sorption of the radionuclides in the geologic medium, delays the release of radionuclides to the accessible environment. An additional assumption was that carbon and iodine are essentially infinitely soluble. Experimental evidence has suggested that carbon released from the wastes may be retarded by an exchange process with natural carbon in the geologic medium. Experiments have also suggested that iodine may be incorporated into certain rock types. As a result, retardation characteristics of the host medium for carbon and iodine may reduce the repository release fractions.

A sensitivity analysis was performed to determine the effects of retardation on release fractions for iodine and carbon. Three additional computer cases were run.

Case 1: Carbon is assumed to have a retardation factor of 5; iodine has a retardation factor of 2. All other assumptions are the same as those used in waste treatment Alternative 1.

Case 2: Carbon is assumed to have a retardation factor of 10; iodine has a retardation factor of 5. All other assumptions are the same.

Case 3: The release of carbon is assumed to be controlled by the dissolution of zirconium metal so that these elements are released equivalently. All other assumptions are the same. No retardation is assumed. This assumes that the principal source of carbon in the wastes results from activation of nitrogen impurities in zirconium metal (which is used for fuel-element cladding).

Results of the sensitivity analysis are shown in Table 7.4. These results are shown to be insensitive to rock type. However, if retardation factors are different for different rock types, the results could be affected by rock type. Results also indicate that the effect of geologic retardation is to delay the releases of carbon and iodine (compared to Table 7.3). Carbon releases are delayed long enough that retardation permits it to decay before it reaches the accessible environment. Iodine releases are also delayed but the half-life of I-129 is long enough that little radioactivity decay occurs. The effect of assuming that carbon is retained in the zirconium and the release of carbon from the waste form is controlled by dissolution of zirconium is to dramatically

TABLE 7.4. Results of Sensitivity Analysis of Carbon and Iodine Retardation

Sensitivity Case/ Element	Fractional Release[a]			
	Reducing Basalt	Reducing Granite and Salt	Oxidizing Granite and Salt	Oxidizing Tuff
1[b]				
Carbon[c]	0	0	0	0
Iodine[d]	0	0	0	0
2				
Carbon[e]	0	0	0	0
Iodine[f]	0	0	0	0
3[g]				
Carbon	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
Iodine	0.0004	0.0004	0.0004	0.0004

(a) Given as the fraction of release limits stated in 40 CFR 191, 10,000 years after repository closure.
(b) See text for descriptions of sensitivity cases.
(c) Release of carbon to the accessible environment is delayed until about 30,000 years.
(d) Iodine release is delayed until 10,000 years but before 20,000 years.
(e) Carbon release is delayed until 60,000 years.
(f) Iodine release is delayed until 40,000 years.
(g) No retardation of carbon or iodine is assumed.

reduce the release to the accessible environment. This again indicates that significant benefits may be derived from a consolidated metal waste form.

7.2 NEAR-TERM PERFORMANCE ASSESSMENT

This section describes in qualitative and quantitative terms the radiological risks associated with handling, processing, and transporting HLW, LLW, and TRU wastes generated in each waste treatment alternative. Risks due to normal or routine radiological exposures and abnormal or accidental radiological exposures are described. The near-term performance (operations phase) of the repository was not included because the study was terminated before this work was completed. However, it is believed that the conclusions derived from this assessment are generally applicable to the near-term performance of the repository, also. The relative differences among processing alternatives that result from repository operations are anticipated to follow the same general trends as the relative risks from waste transportation operations. Reduced waste volumes should reduce near-term occupational risks at the repository because reduced waste volumes will reduce the number of shipments and waste packages to be handled at the repository.

7.2.1 Methodologies, Bases and Assumptions

Normal radiological exposures in waste treatment facilities are the exposures of operating personnel to penetrating radiation that arise from planned practices at the facility. Abnormal radiation exposures are the risks to operating personnel which are caused by abnormal events at the facility. Abnormal events are those events that disrupt routine operations and are serious enough to warrant design features to mitigate adverse effects from such events. The preliminary risk assessment of the waste processing facilities included both HLW and TRU/LLW treatment facilities.

Risks from transportation of the wastes are also categorized as routine and abnormal. Routine risks arise from the exposures of the public and transportation personnel to the very low levels of radiation emitted from the shipping container. Abnormal transportation risks arise from the potential releases of radioactive material from a shipping container that is involved in an accident. The methods, bases, and assumptions used to estimate these risks are described in the following subsections.

7.2.1.1 Normal Exposures from Waste Processing

The total normal exposure resulting from operation of each waste treatment facility concept depends on exposure rates, crew sizes, duration of various operations, and the number of these operations per year. The maximum quarterly exposure received by any individual at the waste treatment facility is established by 10 CFR 20, Section 20.101. This regulation establishes an upper limit of 3 rems per calendar quarter per individual (rem/quarter) as the total occupational dose to the whole body. This limit takes into account the person's age and past dose history.

The exposure of operating personnel to radiation will depend on many factors. These factors include the radioactivity levels of the materials being handled, the shielding between workers and the radioactive materials, and the protective clothing worn by each worker. The exposure rates for various types of waste treatment operations will vary with conditions. Nonetheless, an average exposure rate can be established using the 3 rem/quarter upper dose limit for radiation workers.

It was assumed that an administrative decision was made at the waste treatment facilities to hold quarterly exposures to a value equal to 1/10 of the maximum level established by regulations. This assumed decision created an allowance for inadvertent exposures to personnel involved in accidental or abnormal situations. This assumption was made by the National Committee on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) and has been utilized by other investigators (DOE 1980). This assumption also reduces the maximum permissible dose to radiation workers to 0.3 rem/quarter. This number was used as the basis for estimating the expected average exposure rate during normal operations.

Each individual at the facility was assumed to work 8-hour shifts and 75 shifts per quarter. This corresponds to 600 working hours per individual per quarter (or 2,400 hours per year). Dividing this number into the maximum permissable exposure of 0.3 rem/quarter gives an average exposure rate of 0.5 millirem/hr, which will be expected in all restricted areas of the facilities.

Annual manpower requirements for operating each of the waste treatment alternatives can be determined by estimating the crew sizes, duration of various operations, and the number of these operations per year. This information, along with the assumed exposure rate, was used to determine the annual total radiological exposure to the work force associated with each waste treatment process operation. Since the current level of technical development of some waste treatment concepts is limited, only estimates of manpower requirements were possible.

7.2.1.2 Abnormal Exposures From Waste Processing

The approach used to estimate abnormal radiological risks was to evaluate major radiological accidents and off-standard conditions that could potentially occur in each waste treatment facility concept. A liquid-fed ceramic melter system is used for vitrification of liquid HLW. TRU waste treatment concepts were described previously (see Section 4.0). To simplify the approach, this accident assessment was divided into an assessment of the HLW treatment facility and an assessment of the TRU waste treatment facilities.

This preliminary risk assessment is an evaluation of the treatment facility only and is independent of other facilities or associated processes in the FRP. For some cases, the risk assessment covers major accidents in the waste treatment facility resulting from errors made in other waste processing systems (e.g., the explosion of "red oil" in the mixing or denitration tanks as a result of its formation and subsequent transfer from a waste processing system evaporator). For most cases, however, these types of accidents were determined to be minor.

The methodology used in the radiological accident assessment was to first identify any significant accidents that could occur in the two waste treatment subsystems. This was accomplished by the use of fault tree analysis, one for the HLW vitrification system, and one for each of the six TRU waste treatment alternatives. Significant accidents refer to any accident with the potential for releasing radioactive material outside its primary containment. After identification of the accidents, descriptions were developed for each identified accident. The accident descriptions include detailed scenarios of possible causes, potential consequences, and potential ways to prevent, detect, or mitigate the accident. They also form the bulk of the accident risk assessment. Included in the discussion of the accident scenarios are references in which additional information can be obtained on the accidents or the waste treatment systems.

7.2.1.3 Transportation Exposures and Risks

Routine exposures and accident risks for offsite shipments of HLW and TRU wastes are divided into two categories: occupational and nonoccupational. Occupational exposures are the exposures to radiation that are received by persons as a result of their occupation (e.g., truck drivers, railroad employees). The general public is the nonoccupationally exposed group. Where possible, radiation exposures to these two population groups are presented separately.

The "unit-risk factor" approach was used to estimate transportation radiological exposures for each waste treatment concept. This approach uses unit risk factors (Neuhauser at al. 1984, Wilmot, Madsen and Cashwell 1983), given in units of person-rem/km of vehicle travel, to calculate the risk. Transportation risks are then calculated using the following formula:

$$R = rDS$$

where

R = the total risk (person-rem)
r = a unit risk factor (person-rem/km)
D = the shipping distance (km)
S = the number of shipments

Unit risk factors have been developed for CH-TRU wastes, RH-TRU wastes, hulls and hardware, and solidified HLW (Wilmot, Madsen, and Cashwell 1983). Risk factors for LLW transport are conservatively assumed to be the same as the CH-TRU waste unit risk factors. Separate risk factors are provided for truck and rail transport. The unit risk factors used in this analysis are presented in Table 7.5. The unit risk factors were used to calculate the risks for transporting each waste type produced in each waste treatment alternative. The risks for each waste type were then aggregated to determine a total risk value for each treatment alternative.

Transportation risks were calculated on an annual basis assuming a 1500 MTU/yr reprocessing facility. It was assumed that the one-way shipping distance for HLW was 3,200 km (2,000 miles) and that for LLW was 480 km (300 miles). As shown in Table 7.6, separate risk factors were developed for travel in each of three population zones: rural, suburban, and urban. It was assumed that all shipments travel through predominantly rural areas (90 percent) with lesser amounts of suburban (5 percent) and urban travel (5 percent). One-hundred percent rail shipping is assumed. The annual number of shipments of each waste type were calculated using the assumed shipping container capacities shown in Table 7.6.

2.2.2 Results and Conclusions

The following subsections present the results and conclusions from the near-term performance assessment.

TABLE 7.5. Transportation Unit Risk Factors (person-rem/km)

	HLW by Rail			RH-TRU by Rail		
Hazard Category	Rural	Suburban	Urban	Rural	Suburban	Urban
Normal						
Nonoccupational	2.1E-3	2.1E-3	2.1E-3	4.9E-4	4.9E-4	4.9E-4
Occupational	4.0E-7	4.0E-7	4.0E-7	9.6E-8	9.6E-8	9.6E-8
Accident						
Nonoccupational	1.4E-8	3.0E-5	4.9E-4	7.9E-12	1.6E-8	2.4E-7

	RH-TRU by Truck			CH-TRU by Rail		
Hazard Category	Rural	Suburban	Urban	Rural	Suburban	Urban
Normal						
Nonoccupational	3.3E-5	4.9E-5	6.3E-5	8.6E-4	8.6E-4	8.6E-4
Occupational	5.2E-6	1.1E-5	1.9E-5	1.3E-7	1.3E-7	1.3E-7
Accident						
Nonoccupational	3.1E-12	4.5E-9	1.5E-8	1.5E-15	3.1E-12	4.5E-11

	CH-TRU by Truck			Hulls by Rail		
Hazard Category	Rural	Suburban	Urban	Rural	Suburban	Urban
Normal						
Nonoccupational	2.8E-5	4.3E-5	5.5E-5	2.1E-3	2.1E-3	2.1E-3
Occupational	4.6E-6	1.0E-5	1.7E-5	4.0E-7	4.0E-7	4.0E-7
Accident						
Nonoccupational	7.1E-16	1.0E-12	3.4E-12	2.9E-14	3.2E-12	9.0E-12

Note: Abbreviated scientific notation - 2.8E-5 = 2.8×10^{-5}

TABLE 7.6. Reference Cask Capacities

Waste Type	Transport Mode	Capacity
HLW	Rail	12 canisters
	Truck	1 canister
Hulls	Rail	1 600-gal drum or 4 160-gal canisters
RH-TRU Waste		
< 1R/hr	Truck	14 55-gal drums or 10 80-gal drums or 1 160-gal canister
> 1 R/hr	Rail	21 55-gal drums or 15 80-gal drums or 4 160-gal cans or 1 600-gal drum
CH-TRU Waste	Truck	36 55-gal drums or 32 80-gal drums or 6 160-gal canisters
CH-TRU Waste	Rail	72 55-gal drums or 64 60-gal drums or 16 160-gal cans or 1 600-gal drum
LLW	Rail	96 55-gal drums or 84 80-gal drums or 16 160-gal cans or 1 600-gal drum

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(a) Source: Wilmot et al. (1983)

(b) Source; NRC (1983); adjustments were made to accomodate odd drum sizes (i.e., 80-gal, 160-gal, and 600-gal containers)

7.2.2.1 Routine Risks from Waste Processing

The routine exposures from waste processing at the FRP were calculated from average radiation dose rates and estimates of facility staffing requirements. The type, frequency, and duration of each unit operation and the required crew size for each operation are the essential parameters for performing a detailed staffing estimate. Currently, most of these parameters are not well defined. Nonetheless, the annual manpower requirements were estimated for each waste treatment facility concept using the information in Sections 4.0, 5.0, and Appendix B. The anticipated operating schedule for each waste treatment alternative is summarized in Table 7.7. The table indicates that most waste treatment processes can be operated on a 200-day-per-year and 24-hour-day (3-shifts-per-day) basis. This assessment assumes that all operations, including maintenance, are scheduled for 300 days/year with three 8-hour shifts/day.

The staffing requirements in terms of man-years/year for each waste treatment alternative are shown in Table 7.8. These estimates are based on the estimated number of process operators, radiation monitors, maintenance workers, and foremen needed for each process operation. Staffing requirements developed by others (Anderson et al. 1979) for similar TRU waste treatment operations are also shown for comparison purposes. As shown, these estimates agree fairly well with the current estimates. The estimates presented in this report are about 70 percent to 100 percent higher than those developed by others.

The annual occupational exposures were calculated by multiplying the annual work force times the maximum exposure rate. A conversion factor of 2,400 hrs/yr/individual was assumed in the calculations. Table 7.9 presents the results of these calculations. Annual exposure estimates developed by others are also shown in the table. The results indicate that the radiation exposures generally increase from WPF-1 through WPF-5. The occupational exposures calculated for WPF-5 were calculated to be about 60 percent higher than those for WPF-1. Also, note that WPF-3 and WPF-4 have roughly equal occupational

TABLE 7.7. Waste Handling Capacity and Operating Schedule

Alternative	Annual Process Capacity	Unit Capacity	Operating Schedule
WPF-1(a) (Basic)			
WAIC(b)	18,000 drums	60 drums/d	300 d/yr @ 24 h/d
HLW(c) Vitrification	360,180 kg-glass	1,320 kg-glass/d	272 d/yr @ 24 h/d
SHLW(d) Storage	700 canister/yr 1,400 storage capacity	---	300 d/yr @ 24 h/d
WPF-2			
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1
Compaction	3,183 m^3	3,778 m^3/300 d	202 d/yr @ 24 h/d; 303 d/yr @ 16 h/d
WPF-3			
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1
Compaction	1,082 m^3	1,606 m^3/300 d	202 d/yr @ 24 h/d; 300 d/yr @ 16 h/d
Incineration	2,102 m^3 (214,000 kg)	45 kg/h	198 d/yr @ 24 h/d; 300 d/yr @ 16 h/d
Cementation	822,000 kg	TBD(e)	TBD
WPF-4			
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1
Melting	601,000 kg	1,400 kg/h	198 d/yr @ 24 h/d; 300 d/yr @ 16 h/d
Incineration	214,000 kg	45 kg/h	71 d/yr @ 24 h/d
Cementation	811,000 kg	TBD	TBD
WPF-5			
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1
Hulls Decon	402,000 kg	TBD	TBD
Vibratory Finishing	~192,000 kg	TBD	TBD
Incineration	214,000 kg	45 kg/h	198 d/yr @ 24 h/d; 300 d/yr @ 16 h/d
Cementation	~850,000 kg	TBD	TBD

(a) WPF-1 = Waste Processing Facility - Alternative No. 1
(b) WAIC = Waste Assay, Inspection, and Certification
(c) HLW = High-Level Waste
(d) SHLW = Solidified High-Level Waste
(e) TBD = To be determined

TABLE 7.8. Personnel Requirements for the Five Waste Treatment Alternatives

		Reference 1			Reference 2			
Alternative	Current Annual Process Capacity	Annual Process Capacity	Operating Schedule	Man-Years	Annual Process Capacity	Operating Schedule	Man-Years	Current Man-Years Estimate
WPF-1 (Basic)								
WAIC	18,000 drums	28,000 drums	NA	22	20,000 drums	310 d/yr	22	36
HLW Vitrification	360,100 kg-glass	300,000 kg-glass	300 d/yr; 24 h/d	61	430,000 kg-glass	300 d/yr; 24 h/d	84	72
SIRW Storage	700 canisters/yr 1,400 canisters storage capacity	660 canisters/yr 3,300 canisters storage capacity	300 d/yr; 24 h/d	Included in HLW Vitrification Above	NA	NA		
				Total 83			Total 106	Total 108
WPF-2								
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1	83	Same as WPF-1	Same as WPF-1	106	108
Compaction	3,183 m^3	5,470 m^3	260 d/yr; 16 h/d	17	3,778 m^3	300 d/yr	6	15
				Total 100			Total 112	Total 123
WPF-3								
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1	83	Same as WPF-1	Same as WPF-1	106	108
Compaction	1,082 m^3	1,320 m^3	260 d/yr; 16 h/d	17	1,000 m^3	180 d/yr	NA	15
Incineration	2,102 m^3 (214,000 kg)	4,150 m^3	300 d/yr; 24 h/d	27	1,100 m^3 (212,500 kg)	180 d/yr	NA	27
Cementation	822,000 kg	910,000 kg	100 d/yr; 24 h/d	4	NA	NA	NA	6
				Total 131			Total >106	Total 156
WPF-4								
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1	83	Same as WPF-1	Same as WPF-1	106	108
Melting	611,000 kg	525,000 kg	250 d/yr; 24 h/d	19	640 m^3 (490,000 kg)	275 d/yr; 24 h/d	NA	12
Incineration	214,800 kg	4,150 m^3	300 d/yr; 24 h/d	27	1,100 m^3 (212,500 kg)	180 d/yr	NA	27
Cementation	811,000 kg	910,000 kg	100 d/yr; 24 h/d	4	NA	NA	NA	6
				Total 133			Total >106	Total 153

TABLE 7.8. (Contd)

Alternative	Current Annual Process Capacity	Reference 1 Annual Process Capacity	Reference 1 Operating Schedule	Reference 1 Man-Years	Reference 2 Annual Process Capacity	Reference 2 Operating Schedule	Reference 2 Man-Years	Current Man-Years Estimate
WPF-5								
Basic	Same as WPF-1	Same as WPF-1	Same as WPF-1	83	Same as WPF-1	Same as WPF-1	106	100
Hulls Decontamination	402,000 kg	670 m^3	NA	7	NA	NA	NA	18
Vibratory Finishing	~192,000 kg	NA	NA	NA	NA	NA	NA	18
Incineration	214,000 kg	4,150 m^3	300 d/yr; 24 h/d	27	1,100 m^3 (212,500 kg)	180 d/yr	NA	27
Cementation	~850,000 kg	910,000 kg	100 d/yr; 24 h/d	4	NA	NA	NA	6
				Total >121			Total >106	Total 177

Reference 1 = DOE/ET-0028, Vol. 2 of 5, May 1979; DOE/ET-0029, Vol. 1 of 3, May 1979
Reference 2 = AGNS Staff, 1978), (Anderson, et al., 1979), (Ougell, et al., 1983)
WPF-1 = Waste Processing Facility - Alternative No. 1
WAIC = Waste Assay, Inspection, and Certification
HLW = High Level Waste
SHLW = Solidified High Level Waste
NA = Information not available in the above literature
Current Annual Process Capacity = The reference process capacity defined in the PNL FY-84 waste management system study (see Table 11)

TABLE 7.9. Summary of Annual Occupational Exposures at Waste Processing Facilities

	Annual Occupational Exposures, person-rem/yr					
	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incinceration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
Reference 1	225	245	358	388	>358	>358
Current Estimate	130	148	187	183	213	213
Difference	95	97	171	205	>145	>145

(a) Reference 1 = DOE (1979); used 0.7 rem/quarter allowable dose rate
(b) Information was not available for vibratory finishing facility

exposures. Thus, from this standpoint, exposures resulting from hulls melting appear to be roughly equivalent to those resulting from hulls compaction.

7.2.2.2 Accident Risks From Waste Processing

HLW and Intermediate-level Waste Solidification

The reference process for high- and intermediate-level liquid waste treatment in all alternatives is vitrification in a liquid-fed ceramic melter (LFCM). The major equipment and process descriptions for the waste vitrification system are quite similar to most other LFCM-based systems. As a result, accident assessments for other LFCM systems (Buelt and Partain 1980) were used to identify most of the significant potential accidents for the system described in Appendix B. A fault tree analysis was performed to identify any other potentially significant accidents. The fault tree is shown in Figure 7.2.

After identification of the potential accidents, scenarios were developed to determine the severity of each potential accident. Of the 23 identified accidents, only those that might involve a major release of radioactive materials within the processing cells were selected for further evaluation. Accident scenarios for the 10 major accidents are shown in Table 7.10.

All but one of the 10 major accidents involves releases from the waste vitrification system (primary containment) to the vitrification cell (secondary containment). These accidents would be mitigated by the facility off-gas systems and the design of the vitrification cell to minimize occupational exposures. The only major potential accident involving releases outside the cell that was identified would be the pressurized blowback of radioactive materials through the frit-feed lines to the cell gallery. To prevent this type of accident, all transfer lines from the gallery into the cell must be designed to prevent backflows or siphon effects.

As shown in Table 7.10, design-basis accidents for FRPs or waste solidification facilities are included. These accidents are the most preeminent in the safety review of a facility, although minor and moderate accidents are also important. The design-basis accidents in Table 7.10 are:

- a criticality occurrence in the melter
- rupture of the melter from a molten glass/water steam explosion
- rupture of the feed mixing tank from a "red oil" explosion
- rupture of the melter from a molten salt/water steam explosion.

Of these, the occurrence of a criticality and a molten rupture of the melter from glass/water steam explosion are judged to be impossible.

Criticality in the melter is not a problem for several reasons. First, evidence indicates that the actinides in a typical HLW glass will not precipitate as a sediment (Walker and Riege 1979). The solubility of PuO_2 in HLW glass containing 20 wt% simulated HLW oxides and 10 percent Gd_2O_3 is approximately 1.3 percent. The solubility rises to 4.5 percent if less than 7 percent gadolinia is present. The concentration of PuO_2 in reprocessed waste glass should be an order of magnitude less than the maximum solubility of PuO_2. Even if such a sediment were to form, it would be substantially subcritical due to the predominant neutron absorption characteristics of the actinide mix. Inclusion of the fission products further reduces the criticality multiplication factors.

The potential for rupture of the melter from a molten glass/water steam explosion was eliminated on the basis of analyses by Postma, Chapman, and Buelt (1980) and Robinson and Fry (1981) which established the required conditions for such an explosion. Based on these analyses, the HLW glass has a viscosity that is orders of magnitude greater than the viscisity of liquids that can thermally interact to produce a vapor explosion. In addition, the HLW feed solution contains solids that act as nucleation sites, further eliminating the possibility of a steam explosion.

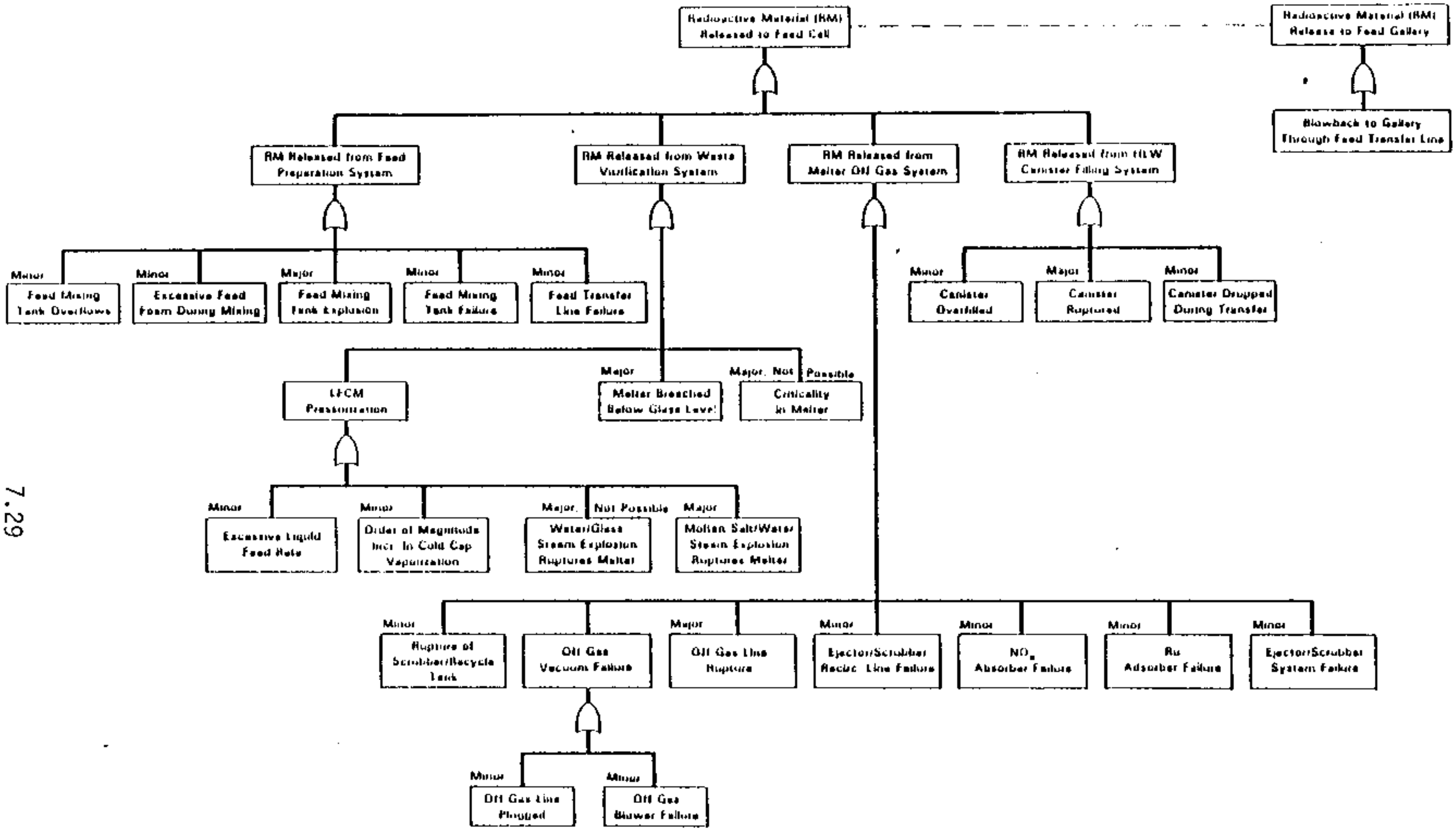

FIGURE 7.2. Fault Tree Analysis for the High and Intermediate Level Waste Vitrification System

TABLE 7.10. Summary of Major Accidents From A LFCM Waste Vitrification System

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
A. LIQUID FEED SPILLS				
Red Oil Explosion in Feed Tank or Denitration Tank	Extremely Improbable. Red Oil is a nitrated compound of degraded solvent.	Feed Tank is ruptured. 100% of feed in tank leaks to cell floor. Explosive forces assumed to atomize 5% of feed.	Tank level indicator. Cell drain sump activity alarms.	Red Oil only forms in evaporators operated outside specifications. The presence of red oil would be detected in the HLLW sampling prior to being transferred to the feed tank. Feed tank is water-cooled below autoignition temperatures. Liquid releases in the cell are collected in sumps. HEPA filters sized to accommodate increased aerosol and particulate loading.
B. POTENTIAL RELEASES FROM LFCM ACCIDENTS				
Severe Molten Salt/Water Steam Explosion Ruptures the Melter	Formation of a thick layer of molten salt on top of the molten glass. Salt layer entraps liquid feed. Superheating of the liquid feed to spontaneous nucleation temperature.	Rupture of the melter containment. All molten glass spills to cell floor. Calcine cold cap dispersed as particulates. 5% of molten glass dispersed as particulate.	Melter instrumentation. Off-gas instrumentation.	The concentration of salts in the HLLW are significantly below solubility limits of the glass. Visual observation of the molten glass surface would indicate substantial salt buildup. HLLW feed has nucleation sites that preclude steam explosion. Off-gas piping and venturi scrubber oversized by a factor of 6 to handle steam surges. Research indicates

TABLE 7.10. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
				that maximum pressurization from explosion would not be greater than 70 psig, worst case conditions (Kuhn 1983). Emergency vents available.
Breach of Melter Containment Box Below Glass Level	Damage from crane operation (e.g., dropping canister on melter).	100% glass spilled on cell floor at 1100°C. Ruthenium and cesium volatilization. Some dispersable glass fines created.	Visual observation during crane operations. Melter off-gas pressure. Melter temperature.	Standard operating procedures. Melter is very rugged. Breach of metal containment would not necessarily cause glass leakage through refractories. Turn off melter power and allow glass to solidify in melter.
Criticality in Melter	Accumulation of critical fissile material via sedimentation or precipitation.	Considered impossible to occur (See Buelt and Partain 1980)	Process sampling.	Considered impossible to occur. Actinides in the HLLW will not precipitate in melter as sediment. Solubility of actinides in glass much higher than HLLW actinide concentrations. Even if sediment could occur, it would be substantially subcritical due to the predominating neutron absorption characteristics of the actinide mix present in glass.
Water/Glass Steam Explosion Ruptures the Melter	Significant volume of liquid injected below the molten glass surface in such a way as to entrap the liquid and superheat it to spontaneous nucleation temperatures.	Experience and theoretical analyses of LFCM's indicate that destructive water/glass interactions are impossible. (See Postma, Chapman, and Buelt 1980).	Feed sampling.	Water/glass steam explosion impossible due to high particulate loading in HLLW feed, and high viscosity of glass.

TABLE 7.10. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
C. POTENTIAL RELEASES FROM OFF-GAS SYSTEM COMPONENT FAILURES				
Break In Off-Gas System Piping	Equipment dropped on piping.	Assume 60 min. of melter off-gas diverted to cell atmosphere. Entrainment from melter of 0.4% volatile RuO_4, 6% particulate RuO_2 and 0.5% total particulate release.	Off-gas instrumentation.	Operation within flowsheet specifications. Melter feed stopped upon loss of off-gas vacuum.
D. POTENTIAL RELEASES FROM GLASS FILLED CANISTER				
HLW Canister Rupture	Weld failure.	Weld failure results in 50% of the glass in the canister spilling to the cell floor. Spill remains at 1000°C for 30 minutes before cooling immediately.	Cell activity detectors visual detection.	QA on canister welds makes incident probability extremely low.
E. RADIOACTIVE MATERIAL RELEASE OUTSIDE PROCESS CELL				
Blowback of HLW Feed to Operating Gallery	Overfilled tank in conjunction with misaligned valving and a pressurization source would force HLLW into glass former addition line.	100 l of HLLW pushed into glass former makeup tank in the operating gallery. Assume 0.1% is entrained in gallery atmosphere.	Feed tank level alarms. Off-gas pressure alarms. Gallery radiation alarms.	Glass former line outlet is above normal tank level. At least one valve located in line. Normal tank pressure below gallery atmosphere pressure.

TRU and LLW Treatment Operations

The purpose of this section is to identify the types of accidents that need to be considered as the complexity of the facilities increases. In general, process complexity increases in order from Alternative 1 to Alternative 5b. Block diagrams for each waste treatment facility concept were shown in Section 4.0. As shown, the more complex alternatives include much, if not all, of the more simple waste treatment processes. In particular, the types of operations and associated accidents found in the PWOT alternative can also be found in all the other alternatives. Other overlaps of the complex alternatives with more simple alternatives are:

- Alternative 3 overlaps Alternative 2 (compaction)
- Alternative 4 overlaps Alternative 3 (incineration)
- Alternatives 5a and 5b overlap Alternative 4 (incineration)
- Alternative 5b overlaps Alternative 5a (metals decontamination)

Potential accidents related to waste processing were identified from the literature. These accidents are described in Table 7.11. The table groups the accidents according to the waste treatment alternative and functional operation given in Section 4.0. To simplify the accident summary, each alternative lists only the accidents that were not listed for the previous less-complex alternatives. Included with each alternative in the table are footnotes identifying the location of the overlapping accident scenarios.

In general, it can be concluded that accident risks increase directly as the facility concept complexity increases. Two important reasons for this conclusion are that 1) accident driving forces (processing pressures and temperatures) are higher in the more complex processes and 2) radionuclide concentrations are higher in the product waste streams for the more complex alternatives. These two effects increase the sizes of potential releases and increases the health effects caused by the potential releases. However, the total risks are expected to be small because the facilities will be designed to prevent or mitigate potential accidents that could result in a release of radioactive material to a normally-occupied area of the facility or to the environment.

TABLE 7.11. Summary of Potential Radiological Accidents for TRU and Low-Level Waste Treatment System

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
A. PACKAGING WITHOUT TREATMENT ALTERNATIVE				
1. Storage				
Over-Pressurization/ Eventual Release of Sealed Canisters (EG&G 1982, Vol. 3; DOE 1979)	Reactive material sealed in drums. Biological, radiolytic, or chemical reaction generates gas. Gasket fails, releasing gas. Building fire.	Spread of contamination; airborne release of TRU contaminated particulate.	Visual examination. Gas detection system (x-ray).	Provisions to vent drums containing combustibles, organics, sludge materials, or waste hulls, if necessary. Reactive material packaged to prevent reaction.
Spontaneous Internal Combustion of a Sealed Drum Occurs (Anderson, et. al. 1979)	Internal heat generation occurs in a canister as a result of reactive material. Internal can temporature raised to spontaneous combustion levels.	Sufficient oxygen present to support combustion of small amount of waste. Neoprene gasket fails. Volatization of ruthenium and other fission products in burned waste.	Visual examination of canister pressurization.	Provision to vent drums containing combustibles, organics, sludge materials, if necessary. Reactive material not routinely packaged with combustibles. Neoprene gasket designed to not fail under these conditions.
2. Inspection Operations				
Waste Hull Canister Dropped, Breached, or Spilled (DOE 1979, Vol. 2)	Hulls canister dropped by crane. Forklift fork penetrates barrels. Forklift drops canister.	Canister breached by fall. 100% of the hulls escape the container. Large amount of the waste volume available for entrainment as fines. Small amount of fines actually entrained.	Visual detection.	Crane inspected prior to use. Crane height limited to minimize impact force. Forklift designed for drum handling. Sand matrix minimized exposed fine material.

TABLE 7.11. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
TRU Waste Drum (No Hulls) Dropped, Breached, of Spilled (DOE 1979, Vol. 3)	Same as waste hull canister.	Fall breached canister. 100% of the general process trash escapes the container. Small amount available for entrainment. Smaller amount of released contents entrained.	Visual detection.	Crane inspected prior to use. Crane height limited to minimize impact force. Forklift designed from drum handling. Drums designed to survive 9 meter drop.
Ignition of Open Barrel of Waste During Interior Inspection (DOE 1979, Vol. 2)	Open barrel comes in contact with flame. Combustibles and organics ignite. Open barrel self-ignites.	Fire slows. Small volume of trash burned before being extinguished. System entrainment of ruthenium, and other fission products in burned waste.	Fire detection system.	Fire immediately put out by suppression system. Only one barrel open at a time. Self igniting materials not normally placed in drum with combustibles.
3. Assay Operations				
Abnormal Radiation Release (W-Rays or Neutron Source) From Assay Facility to Operating Personnel (Anderson, et. al. 1979)	Failure of x-ray protection equipment. Breach of encapsulation barriers surrounding neutron detection source.	Very unlikely. If breach occurs, only a small amount of neutron source released.	Activity detectors. Dosimetry.	Very unlikely. Radiation containment in assay facility designed to protect operating personnel.
4. Overpacking Operations				
Ignition of Fire Resulting from Welding of Overpacking Container (EG&G 1982)	Sparks from welding operation ignite TRU or low level waste materials.	Spread of some contamination. Possible release of entrained radioactive material.	Fire detection system.	Fire suppression system. Overpack welding area separated from other waste treatment stations by fire wall.

TABLE 7.11. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
B. PACKAGING WITH COMPACTION Additional Risks to the Packaging Without Treatment Alternative (See A.)				
1. Drum Dumping				
Waste Hull Canister Spill While Dumping (DOE 1979, Vol. 2)	Canister dropped during handling. Operator error results in spill to the floor instead of to the dumping tank.	100% of the hulls in canister spilled to the floor. Fraction of waste in canister available for entrainment as fines. Very small amount of actual fine entrainment. Airborne contamination.	Visual detection.	Sand matrix minimizes exposed fine material. Drum dumping station designed to minimize spills, entrainment.
TRU Waste Drum Spilled While Dumping (DOE 1979, Vol. 3)	Same as waste hull canister (see above).	100% of waste in drum spilled to floor. Small amount available for entrainment. Smaller amount of released contents entrained. Airborne contamination.	Visual detection.	Drum dumping station designed to minimize spills and entrainment.
2. Shredding Operations				
Potential Ignition/ Combustion of Combustibles (Klingler 1981)	Fire or explosion caused by excessive dusting; explosive or reactive constituent in feed. Jam-up of materials causes sparking or friction.	Aerosols, volatiles, and soot in enclosure. Possible rupture of chamber. Room contamination. Personnel Exposure.	Fire detection system.	Fire suppression system. Normal low dust operations of shredder. Administrative control of feed. Visual observation.

TABLE 7.11. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
3. In Can Compaction				
Ignition of Zircalloy Fines During Compaction of Waste Hull Canisters (DOE 1979, Vol. 2; Klingler 1981)	Generation of pyrophoric fines from compaction operation. fines ignite from sparking and exposure to air of unoxidized zircalloy surface fines.	Fire in waste hull canister. Fire may also ignite other previously created fines. Potential release of airborne contamination.	Fire detection system.	If hull surfaces are clean, free of oxides, compaction bonds the surfaces together under sufficient pressure to encase all but the surface fines. Fines should not be processed by compaction
Criticality Occurrence	Compaction reduces volume 1.6 - 4.0 times (McCarthy, 1984)	Considered very unlikely to occur. Compaction does not increase effective criticality enough as the waste is just compacted, not changed.	Potential detected during assay.	Waste assayed to make certain that the minimum critical mass is not present in each container.

C. INCINERATION/CEMENTATION PLUS COMPACTION

Additional Risks to the Packaging Without Treatment Alternative (See A.) and Packaging with Compaction Alternative (See B.)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
1. General Process Trash Segregation				
Glove and/or Skin Tear During Sorting and Segregation	Sharp items (glass, sharp metal) found during segregation. Cuts through gloves and finger or hand.	Skin and Possible internal contamination to operating personnel.	Radiation monitoring survey upon exiting radiation zone.	Glove designed to minimize cuts, tears. Operator wears 2nd pair surgeon's gloves when hands are inside the contamination gloves.
2. Incineration				
Fire or Explosion In Incineration Feed Preparation System (Klingler 1981; DOE 1979, Vol. 2)	Fire starts in trash awaiting incineration or small amount of explosive material in incinerator feed. Failure of fire suppression system.	Burning of a large fraction of the entire incineration inventory. Entrainment of airborne radionuclide contamination.	Fire Detection System.	Fire suppression system. Cell filters located away from incinerator. Explosives not used in incineration.

TABLE 7.11. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
Explosion in Incinerator From Incinerator of Flameout Followed by Explosive Re-ignition, (Klingler 1981; DOE 1979, Vol. 2)	Flame-out occurs in incinerator. Explosive re-ignition of fuel-air mixture leads to breach of incinerator. Incinerator control system fails to detect loss of flame allowing accumulation of unburned feed prior to re-ignition.	60% of ash in incinerator at maximum load is suspended in cell air. Aerosols volatiles and soot released to air.	Incineration control system. Combustion analyzer should detect combustibles and shut off feed.	Incinerator control system greatly reduces probability of occurrence. Automatic fire control sprinklers would activate, reducing airborne particles.
Explosion in Incinerator Resulting from Improper Combustion of Feed (Klingler 1981; DOE 1979, Vol. 2)	Explosive of violent reactive constituent in feed. Overfeeding of combustibles.	Possible rupture of incinerator chamber. Aerosols, volatiles, and soot released to air.	Incinerator or control system. Combustion analyzer should detect overfeeding and shut off feed.	Incinerator control system greatly reduces chance of occurrence. Automatic fire control and sprinklers would activate, reducing airborne particles. Waste organics in feed limited by process requirements.
Fire or Explosion From Leaking Fuel or Organic Feed Outside of Incinerator (Klingler 1981)	Delivery system leakage coupled with ignition by sparks or chamber radiant heat.	Particles, aerosol, ash, soot released to enclosure and service duct. Possible release to room.	Liquid leaks visually detected.	Fire extinguishing system in enclosures. Leaks repaired. System designed and inspected to be free of leaks.
3. Incineration Off Gas Treatment				
Explosion In Off Gas Train Resulting From Re-ignition of Flammable Vapors (Klingler 1981)	Organic volatiles introduced because of incomplete combustion.	Particles and aerosol released in enclosures and in service duct for exhaust. Possible rupture of duct with resulting contamination release. Possible flow interruption. Occupational exposure to radioactivity.	Gas analyzer detection system.	Combustion gas analyzer shuts down incinerator if explosive levels of organic vapors are present. Ignition source in off gas is unlikely. Scrubber solution spray is available to reduce organic volatiles.

TABLE 7.11. (Contd)

Incident	Possible Causes	Potential Consequences	Detection	Prevention/Mitigation
Criticality in Scrub Concentration Tank (Klingler 1981)	Accumulation of excessive fissile material in a geometrically unsafe location. Insoluble sludge settles in tank and goes undetected.	Fission products, noble gases, and volatiles released. Low probability of occurrence. Significant onsite and offsite consequences with occurrence.	Scrub liquor monitoring for activity.	Vessel fabricated with bottom outlet drains to remove sludge. Vessel agitated to prevent sludge buildup. Tank routinely emptied. Very low probability of occurrence.
4. In Drum Cementation/Ash Treatment				
Criticality in Incinerator Ash or Cementation Form (Klingler 1981)	Incineration of combustibles accumulates an ash residue that can become concentrated with fission products. Moderator added to ash during cementation.	Considered very unlikely to occur, but significant onsite and offsite consequences if it does.	Detection of quantity of critical material in ash assay.	Incinerator emptied after each batch. Amount of material loss easily detected by material balances. No moderator available in incinerator. Amount of critical material in each ash batch limited to below minimum critical mass for each cemented drum.
Ash Spill/Excessive Entrainment During Mixing of Handling	Movement of ash results in excessive entrainment while handling or spilling or ash and ash mixing with dry cement.	Entrainment of excessive amounts of airborne radionuclide particulate.	Airborne activity detectors and visual detection.	Constant wetting of ash/cement mixture minimizes entrainment. Water sprays available in ash handling area.

7.2.2.3 Transportation Accident Risks and Routine Exposures

The results of the transportation risk assessment for each waste treatment alternative are presented in Table 7.12. These results are illustrated in Figure 7.3. The waste treatment alternatives would be ranked, based on total annual transportation risks, in the following order:

1. Alternative 4 (lowest risk)
2. Alternative 5b
3. Alternative 3
4. Alternative 2
5. Alternative 5a
6. Alternative 1 (highest risk)

In general, transportation risks are dominated by HLW transportation risks. The percentage of the risks in each case that were attributable to HLW transportation ranged from a low of about 50 percent (Alternative 1) to a high of about 90 percent (Alternative 4) of the total risks. Alternative 2 (compaction) has significantly lower transport risks than Alternative 1 (PWOT), primarily because of the reduced volume of cladding hulls and hardware. Alternative 3, which includes incineration of combustible wastes, did not show a significant reduction in tranportation risks, which indicates there is no incentive with respect to transportation risks to incinerate the TRU wastes. Alternative 4 has the lowest transportation risks, which indicates there is a significant incentive to reduce the volume of hulls and hardware as much as possible. Note that in Alternative 5b transport risks are second highest because the volume of HLW has been increased above the other waste treatment alternatives by adding combustible GPT and filter media to the LFCM feed stream. Since HLW transportation contributes the largest fraction of the total annual risks for each alternative, a relatively large increase in transportation risks for Alternative 5a occurs.

TABLE 7.12. Annual Transportation Risks for Each Waste Treatment Alternative

Waste Type	Annual Transportation Risks, person-rem/yr					
	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incineration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
HLW	390	390	390	390	600	390
RH-TRU waste	250	53	74	34	30	33
CH-TRU waste	78	25	19	0	8	0
LLW	82	68	35	21	45	46
Total (rounded)	800	540	520	450	680	470

(a) Includes sum of routine and accident risks for both occupational and nonoccupational population groups.

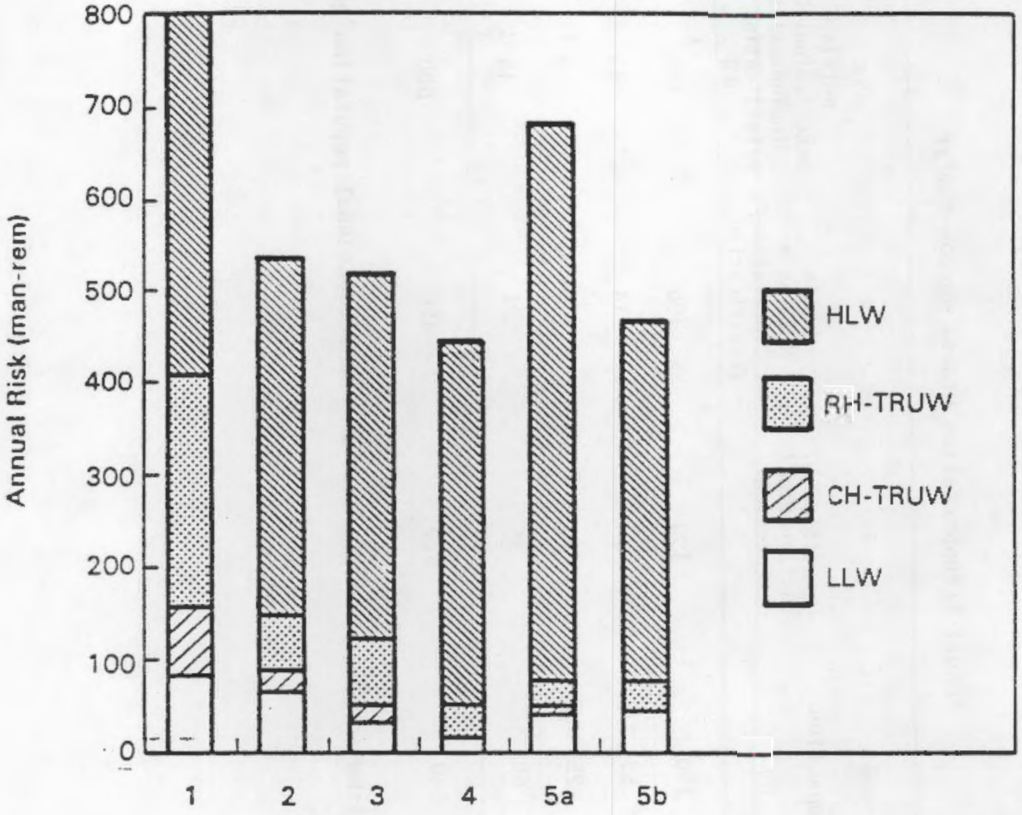

FIGURE 7.3. Annual Transportation Risks for Each TRU Waste Treatment Alternative

8.0 WASTE MANAGEMENT SYSTEM COST ANALYSIS AND OVERALL COMPARISON OF WASTE TREATMENT ALTERNATIVES

The total costs of treatment, transportation, and disposal of solidified HLW, TRU wastes, and LLW generated at a fuel reprocessing plant are estimated in this section. Total system costs are an essential element of this study because a cost reduction resulting from TRU waste processing in one component of the waste management system may affect the costs other components. This section is organized into separate sections for waste treatment, transportation, and disposal cost estimates. The fourth section is provided to discuss the total waste management system costs. The final section presents an overall comparison and ranking of the waste treatment alternatives, based on the results of the performance assessment and the cost analysis.

8.1 WASTE TREATMENT COSTS

This section presents estimates of the capital and operating costs for the processes and facilities that may be required at a FRP to treat radioactive wastes. The WPF concept considered in this study is that of a separate facility from the FRP. The WPF is an integrated concept where the various waste treatment processes share service facilities such as cranes, crane maintenance cells, remote maintenance cells, laboratories, control rooms, offices, change rooms, ventilation systems, utilities, security services, and the WPF building. Much of the cost data used herein was taken from previous conceptual designs of facilities to handle liquid and solid wastes that would have been generated at the BNFP. As a result, the cost information presented in this section is focused on changes and additions made to the BNFP conceptual designs. Detailed descriptions of the alternative WPF concepts and the amounts of waste generated were presented in Sections 5.0, 6.0, and Appendices B and C.

Waste treatment costs are the sum of capital and operating costs. Capital costs include the direct costs for major equipment (tanks, vessels, melters, etc.), bulk materials (including concrete, structural materials, pipe, liner plates, etc.), and construction labor plus indirect costs for engineering, fees, and other distributable costs. A 25 percent contingency was added to the direct and indirect capital costs. Capital cost estimates for each WPF concept are provided in Appendix B.

Operating costs include salaries, fringe benefits, overheads, utilities, supplies, and other fixed and variable annual costs. Direct operating labor costs are calculated from estimates of the operating man-power requirements (see Table 7.9). Man-power requirements were multiplied by annual man-power costs (assumed to be $71,300/man-year for direct operating labor costs and $43,700/man-year for support labor). In all cases, it was assumed that 1.95 man-years of support labor are required for each man-year of direct operating labor. All costs are presented in mid-1984 dollars.

Total life-cycle (70,000 MTU-equivalent) waste treatment costs are calculated in Section 8.4.

8.1.1 Package-Without-Treatment Alternative (WPF-1)

The minimum facilities required for reprocessing waste treatment is defined when the wastes are packaged without treatment. In this alternative, the WPF contains facilities for 1) HLLW and ILLW solidification; 2) WAIC; 3) solidified HLW storage; 4) hulls storage; 5) CH-TRU waste storage; and 6) RH-TRU waste storage. These facilities were described in Section 5.1.

A breakdown of the cost estmates for WPF-1 is shown in Table 8.1. These cost estimates were escalated to mid-1984 dollars using an escalation factor of 1.03 (cost estimates were given in Appendix B in mid-1983 dollars). As shown, capital costs for WPF-1 were estimated to be $227 million, and total operating costs were approximately $21.6 million/yr.

TABLE 8.1. Capital and Operating Cost Estimates for WPF-1

Facility	Capacity	Capital Cost		Operating Cost, $ millions/yr			
		$ Millions	Reference	Fixed	Variable	Support	Reference
HLLW and ILLW solidification	Hydraulic - 200 L/hr Glass - 1320 kg/day	166	a	1.3	6.2	---	d
Hulls Storage (pre-assay)	12,000 cu. ft.	9	b	0.7	---	---	b,c
Hulls Storage (post-assay)	12,000 cu. ft.	10	b	0.7	---	---	b,c
WAIC	18,000 drums/yr	31	d	---	1.7	---	b,c
CH-TRU Storage pre & post assay	1,600 drums	1	b	0.6	----	---	b,c
RH-TRU Storage pre & post assay	900 drums	6	b	0.6	---	---	b,c
Other		5		0.3	---	9.5	
Total		227		4.2	7.9	9.5	

(a) Costs are given in mid-1984 dollars.

(b) References are as follows: a = Rogell and Stenbeck 1983; b = AGNS 1978; c = Memorandum from W. Knox, of AGNS, to L. R. Dodd, PNL, 1983.

(c) WAIC costs consist of $20 million (from Knox, ANGS) plus $10 million to accomodate hulls assay facilities (PNL estimate).

(d) Based on 1.95 man-yrs of support labor for each man-yr of direct operating labor.

TABLE 8.2. Capital and Operating Cost Estimates for WPF-2

Facility	Capacity	Capital Cost		Operating Cost, $ millions/yr			
		$ Millions	Reference	Fixed	Variable	Support	Reference
HLLW and ILLW solidification	Hydraulic - 200 L/hr Glass - 1320 kg/day	166	a	1.3	6.2	---	d
Hulls Storage (pre-assay)	12,000 cu. ft.	9	b	0.7	---	---	b,c
Hulls Storage (post-assay)	3,800 cu. ft.	5	b	0.7	---	---	b,c
WAIC	18,000 drums/yr	31	d	---	1.7	---	b,c
CH-TRU Storage pre & post assay	960 drums	1	b	0.6	----	---	b,c
RH-TRU Storage pre & post assay	550 drums	1	b	0.6	---	---	b,c
Compaction	18,000 drums/yr	41	c	0.7	1.3	---	c
Other		5		0.3	---	9.5	
Total		259		4.9	9.2	10.7	

(a) Costs are given in mid-1984 dollars.

(b) References are as follows: a = Rogell and Stenbeck 1983; b = AGNS 1978; c = Memorandum from W. Knox, of AGNS, to L. R. Dodd, PNL, 1983.

(c) WAIC costs consist of $20 million (from Knox, ANGS) plus $10 million to accomodate hulls assay facilities (PNL estimate).

(d) Based on 1.95 man-yrs of support labor for each man-yr of direct operating labor.

8.1.2 Compaction Alternative (WPF-2)

The second waste treatment facility concept includes provisions for compaction of cladding hulls and hardware and other compactible wastes. This process reduces waste volumes but does not affect waste form stability. This is essentially the same facility as WPF-1 with the addition of a compaction facility and associated support services.

Cost estimates for WPF-2 include the costs of all of the facilities in WPF-1 except for adjustments for reduced treated waste storage requirements plus the compaction facility costs. Capital and operating cost estimates for WPF-2 are summarized in Table 8.2. As shown, total capital costs are estimated to be about $259 million and total operating costs are estimated to be $24.8 million/yr.

8.1.3 Compaction Plus Incineration/Cementation Alternative (WPF-3)

This concept provides additional volume reduction by incinerating combustible wastes rather than compacting them. The ash from the incinerator system is combined with concentrated incinerator off-gas scrubber solution and particulate solids in a cemented waste form. This concept improves the stability of the combustible waste materials. Compaction capabilities, although at lower capacities, are still provided for wastes that are campactible but not combustible. WPF-3 contains all the facilities contained in WPF-2 with the addition of an incineration/cementation system. Adjustments were made in the WPF-3 cost estimates to reflect reduced treated waste storage requirements.

Table 8.3 contains a breakdown of the capital and operating costs for each component of WPF-3. As shown, total capital costs are estimated to be $276 million. Total operating costs are approximately $29.7 million/yr.

TABLE 8.3. Capital and Operating Cost Estimates for WPF-3

Facility	Capacity	Capital Cost $ millions	Capital Cost Reference	Operating Cost, $ millions/yr Fixed	Variable	Support	Reference
HLLW and ILLW solidification	Hydraulic - 200 L/hr	166	a	1.3	6.2	---	e
Hulls Storage (pre-assay)	12,000 cu.ft.	9	b	0.7	---	---	b,c
Hulls Storage (post-assay)	3,800 cu.ft	5	b	0.7	---	---	b,c
WAIC	18,000 drums/yr	31	c	---	1.7	---	b,c
CH-TRU storage pre & post assay	940 containers	1	b	0.6	---	---	b,c
RH-TRU storage pre & post assay	650 containers	1	b	0.6	---	---	b,c
Compaction	1,800 containers/yr	21	c	0.7	0.8	---	c
Incineration/ cementation	45 kg/hr	37	d	0.4	2.4	---	d
Other		5		0.3	---	13.3	
Total		276		5.3	11.1	13.3	

(a) Costs are given in mid-1984 dollars.

(b) References are as follows: a = Rogell and Steneck 1983; b = AGNS 1978; c = Anderson and Evans 1983; d = Evans and Mitchell 1983; e = Memorandum from W. Knox, AGNS, to L. R. Dodd, PNL, 1983.

(c) WAIC costs consist of $20 million from Knox (1983) plus $10 million to accommodate hulls assay facilities (PNL estimate).

(d) Based on 1.95 man-yrs of support labor for each man-yr of direct operating labor.

8.1.4 Metals Melting Plus Incineration/Vitrification Alternative (WPF-4)

This concept includes facilities for melting of metallic wastes and incineration/vitrification of combustible wastes. Metallic solids from the incineration process are melted along with other metallic wastes. The ash plus HEPA filter media from the incinerator is combined and added to the LFCM to provide some of the inert materials needed for the vitrification process. No waste compaction facilities are provided in this concept. Further details regarding this WPF concept are presented in Appendix B.

The capital and operating cost estimates for WPF-4 are presented in Table 8.4. As shown, total capital costs are estimated to be $299 million and total operating costs are approximately $29.7 million.

8.1.5 Metals Decontamination Plus Incineration/Vitrification Alternative (WPF-5a and 5b)

In this concept, facilities are provided to decontaminate most of the metallic wastes so they can be disposed of as LLW rather than TRU waste. Secondary wastes resulting from decontamination are vitrified along with the HLW and incinerator ash and HEPA filter media resulting from incineration of combustible wastes. The incinerator off-gas scrubber solution and some of the particulate solids are incorporated into a cement matrix. No metals melting or compaction facilities are included in this concept.

The primary difference between treatment Alternatives 5a and 5b is that a separate TRU waste glass is produced in Alternative 5b. The TRU waste glass includes the metals removed during the decontamination process and the flourinator solids, the incinerator ash and the filter media. In case 5a, the incinerator ash and filter media are incorporated in the HLW glass. This increases the total volume of HLW glass produced. Capital and operating costs for both cases 5a and 5b are approximately the same.

Table 8.5 contains a breakdown of the cost estimates for WPF-5a and WPF-5b. The total capital costs were estimated to be $316 million and operating costs were estimated to be about $31.6 million.

TABLE 8.4. Capital and Operating Cost Estimates for WPF-4

		Capital Cost		Operating Cost, $ millions/yr			
Facility	Capacity	$ millions	Reference	Fixed	Variable	Support	Reference
HLLW and ILLW solidification	Hydraulic - 200 L/hr Glass - 1320 kg/day	166	a	1.3	6.2	---	e
Hulls Storage (pre-assay)	12,000 cu. ft.	14	b	0.7	---	---	b,c
Hulls Storage (post-assay)	1,600 cu. ft.	3	b	0.7	---	---	b,c
WAIC	18,000 drums/yr	31	e	---	1.7	---	b,c
CH-TRU storage pre & post assay	890 containers	1	b	0.6	---	---	b,c
Incineration/ vitrification	45 kg/hr	36	c	0.4	0.8	---	c
Hulls Melting	100 kg/hr	42	d	1.2	2.2	---	d
Other		5		0.3	---	13.0	
Total		299		5.8	10.9	13.0	

(a) Costs are given in mid-1984 dollars

(b) References are as follows: a = Rogell and Steneck 1983; b = AGNS 1978; d = Memorandum from P. Ebel, AGNS to R. W. McKee, PNL, August, 1983; e: Memorandum from W. Knox, AGNS, to L. R. Dodd, PNI, 1983.

(c) WAIC costs consist of $20 million plus $10 million to accommodate hulls assay facilities (PNL estimate).

(d) Based on 1.95 man-yrs of support labor for each man-yr of direct operating labor.

TABLE 8.5. Capital and Operating Cost Estimates for WPF-5a and WPF-5b

Facility	Capacity	Capital Cost		Operating Cost, $ millions/yr			
		$ millions	Reference	Fixed	Variable	Support	Reference
HLLW and ILLW solidification	Hydraulic - 200 L/hr Glass - 1320 kg/day	166	a	1.3	6.2	---	d
Hulls Storage (pre-assay)	12,000 cu. ft.	14	b	0.7	---	---	b,c
WAIC	10,000 drums/yr	31	d	---	1.7	---	b,c
CH-TRU storage pre & post assay	980 containers	1	b	0.6	---	---	b,c
Incineration/ vitrification	550 containers	36	c	0.4	0.8	---	c
Centrifugal barrel; decon	424,000 kg/yr	43	e	---	3.4	---	c
Vibratory finishing decon	175,000 kg/yr	19	e	---	0.5	---	e
Other		5		0.3	---	15.1	
Total		316		3.9	12.6	15.1	

(a) Costs are given in mid-1984 dollars

(b) References are as follows; a = Rogell and Steneck 1983; b = AGNS 1978; c = Memorandum from W. Knox, AGNS, to L. R. Dodd, PNL, 1983; e = PNL estimate.

(c) WAIC costs consist of $20 million plus $10 million to accommodate huss assay facilities (PNL estimate).

(d) Based on 1.95 man-yrs of support labor for each man-yr of direct operating labor.

8.2 TRANSPORTATION COSTS

The costs for transporting radioactive wastes to a repository is a substantial portion of the waste management system costs. Basic cost information is presented in this section for transporting HLW, LLW, CH-TRU and RH-TRU wastes. Total system transportation costs over a 70,000 MTU-equivalent capacity repository life-cycle are presented later in Section 8.4.

It is assumed in this study that transportation services will be provided by commercial carriers. Transportation costs are assumed to be the sum of two factors: 1) shipping cask lease fees and 2) freight charges. In general, each waste material requires a different shipping container (or cask) because of the differences in radiological and thermal properties of the cargo. Table 8.6 presents much of the basic shipping cask information used in this analysis. Note that no shipping casks are designed specifically to transport 600-gal drums and 80-gal drums. The characteristics of casks designed for smaller waste containers were adapted for these larger sizes and used in this analysis. Furthermore, it was assumed in the cost calculations that all shipments of HLW and cladding hulls were made by rail. All shipments of 600-gal drums, as well as RH-TRU wastes with a surface dose rate greater than 1 R/hr, are also shipped by rail. All other shipments are assumed to be by truck.

Calculation of transport costs for HLW and TRU wastes were based on a 3,200 km (2,000 mile) one-way shipping distance from the FRP to the repository. LLW transport costs are based on a 480 km (300 mile) one-way distance because LLW burial grounds will be much closer to the FRP than the repository. The average rail speed was assumed to be 19.2 km/hr (12 mph) for 24 hours per day (Wilmot, Madsen, and Cashwell 1983). Truck shipments of HLW, RH-TRU wastes, and cladding hulls are assumed to travel 24 hours per day (using two truck drivers) at an average speed of 56 km/hr (35 mph). Other waste types travel at the same average speed but are assumed to travel only 12 hours per day (using one truck driver). Truck and rail turnaround times are assumed to be 3 days per truck shipment and 5 days per rail shipment (Wilmot, Madsen, and Cashwell 1983).

TABLE 8.6. Transportation Parameters

Waste Type	Transport Mode	Capacity	Empty Wt., lbs.	Loaded Wt., lbs.	Captial Cost $ millions	Lease fee, $/day	Turnaround time, days	Round-trip transit time, days
HLW	Rail	12 canisters	158,000	179,000	1.8	1,800	5	24
	Truck	1 canister	36,600	38,500	1.1	1,100	3	11
Hulls	Rail	1 600-gal drum or 4 160-gal canisters	156,000	200,000	1.8	1,800	5	24
RH-TRU Waste								
< 1R/hr	Truck	14 55-gal drums or	33,900	40,500	NA	200	2	14
		10 80-gal drums or	33,900	37,400	NA	200	2	14
		1 160-gal canister	39,000	43,000	1.1	1,100	3	16
< 1R/hr	Rail	21 55-gal drums or	106,200	116,100	NA	600	5	24
		15 80-gal drums or	106,200	111,600	NA	600	5	24
		4 160-gal canisters	156,000	170,000	1.8	1,800	5	24
CH-TRU Waste	Truck	36 55-gal drums or	33,000	60,000	0.7	700	2	14
		32 80-gal drums or	33,000	42,200	0.7	700	2	14
		6 160-gal canisters	33,000	50,000	0.7	700	2	14

(a) Source: Wilmot, Madsen, and Cashwell (1983)

(b) Cask lease rates were calculated assuming a 25% annual capital charge. Maintenance and service charges are assumed to amount to 5% of the initial capital costs per year

(c) Round-trip transit times calculated for a 2,000-mile one-way shipping distance.

(d) Hulls rail cask is also used to transport 600-gal. drums and 160-gal. RH-TRU waste canisters.

(e) RH-TRU wastes less than 1 R/hr are shipped by truck in CNS14-170 (NRC 1983); greater than 1 R/hr are shipped by rail in CNS7-100 (three casks per rail car)

(f) Daily lease rate obtained by telephone contact with cask supplier company.

(g) Assumed to use TRUPACT shipping container.

Truck freight charges are based on published tariffs from a commercial radioactive material shipping company. Rail freight charges are calculated from information published by Daling and Engel (1983). These charges are based on the shipping distance and the empty and loaded weights of the shipping containers.

The unit transportation costs for each waste type are presented in Table 8.7. The total system transportation costs are calculated by multiplying the unit transportation costs times the total number of shipments required to transport the amount of waste generated by reprocessing 70,000 MTU of spent fuel. The total number of shipments required to dispose of 70,000 MTU-equivalent of HLW, TRU waste, and LLW are presented in Table 8.8.

8.3 REPOSITORY AND LLW DISPOSAL COSTS

This section describes the bases used for calculating repository disposal costs for HLW and TRU wastes and the costs for disposing of LLW in a shallow-land burial facility.

8.3.1 Repository Disposal Costs

Disposal costs for HLW and TRU wastes were calculated using the RECON computer program (Clark et al. 1983). RECON models the life-cycle construction and operating costs of deep geologic repositories. The model consists of subroutines that describe repository construction and operation using about 800 variables of which 200 are input variables. The variables describe such items as labor requirements, materials costs, utilities, capital costs, wage rates, equipment costs, processing rates, rock excavation, backfilling, sealing, decommissioning, and waste receiving, packaging, onsite transport, and emplacement operations. Other parameters describe site preparations, surface facilities, mine layout, and repository capacity. The model differentiates between each waste type received by the repository in terms of the quantity received, shipping cask capacities, transport mode, heat generation rates, type

TABLE 8.7 Unit Transportation Costs

Waste Type	Waste Container	Transport Mode	Unit Costs $/shipment
HLW	Canister	Rail	106,000
RH-TRU Waste			
< 1 R/hr	55-gal drum	Truck	14,000
	80-gal drum	Truck	14,000
	160-gal can	Truck	21,000
	600-gal drum	Rail	57,000
> 1 R/hr	55-gal drum	Truck	8,700
	80-gal drum	Truck	8,700
	160-gal can	Rail	72,000
	600-gal drum	Rail	57,000
CH-TRU Waste	55-gal drum	Truck	25,000
	80-gal drum	Truck	30,000
	160-gal can	Truck	19,000
	600-gal drum	Rail	57,000
LLW-unshielded	all containers	Truck	2,000
LLW-shielded	55- and 80-gal drums	Truck	4,000
	160-gal can	Truck	4,000
	600-gal drum	Rail	28,000

(a) See Table 8.6 for reference shipping cask parameters

(b) This category is for LLW containers with surface dose rates greater than 200 millirem/hr

TABLE 8.8. Number of Shipments in Each Alternative

Waste Type	Transport Mode	Waste Container	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5a	Alt.5b
			Number of Shipments/70,000 MTU					
HLW	Rail	Canister	1,800	1,800	1,800	1,800	1,800	1,800
RH-TRU Waste								
< 1 R/hr	Truck	55-gal drum	660	310	577	552	613	---
	Truck	80-gal drum	504	---	---	---	---	---
	Truck	160-gal can	---	1,991	567	---	---	---
	Rail	600-gal drum	1,354	47	47	---	---	---
> 1 R/hr	Truck	55-gal drum	621	---	1,508	---	225	---
	Truck	80-gal drum	234	---	---	---	---	---
	Rail	160-gal can	---	2,811	2,390	1,130	---	1,266
	Rail	600-gal drum	16,613	140	140	---	---	---
CH-TRU Waste	Truck	55-gal drum	856	91	111	---	231	---
	Truck	80-gal drum	1,624	---	---	---	---	---
	Truck	160-gal can	---	493	121	---	---	---
	Rail	600-gal drum	187	187	187	---	---	---
LLW-unshielded	Truck	55-gal drum	9,353	2,664	3,150	3,232	4,279	4,347
	Truck	80-gal drum	149	---	---	---	---	---
	Truck	160-gal can	---	2,972	1,064	---	---	---
	Rail	600-gal drum	304	292	292	---	---	---
LLW-shielded	Truck	55-gal drum	788	546	---	---	21	21
	Truck	80-gal drum	74	---	---	---	---	---
	Truck	160-gal can	---	623	---	---	30,660	30,660
	Rail	600-gal drum	140	---	---	---	---	---

(a) Based on annual waste generation rates from Section 6.0 and reference shipping cask capacities from Table 8.6.

of handling required (i.e., contact or remote), package or overpack dimensions, throughput rates, and emplacement parameters. Based on input constraints such as maximum repository heat loading or minimum canister spacing, the model calculates emplacement densities, excavation requirements, and operating periods. This information is used with the input data previously described to generate cost estimates for each phase of repository operation from construction through decommissioning. Contingency costs representing the uncertain costs of labor, materials, and other items are added by multiplying costs by a contingency factor.

Repository disposal costs are calculated in this study based on disposal in a commercial salt repository. Design details for the commercial salt repository were reported by Stearns - Rogers (1983). Cost estimates were prepared for two cases. Case 1 assumes that TRU wastes will be co-emplaced in the same rooms as the HLW canisters. This practice will reduce the mining requirements and costs. However, it is believed that the NRC will require long-lived packagings on wastes in high-heat repository zones. Therefore, for Case 1, it was assumed that thick, long-lived carbon steel overpack canisters would be placed around the TRU wastes as well as around the HLW. In Case 2, the TRU wastes and HLW were assumed to be emplaced in separate rooms in the repostory. This was assumed to eliminate the requirement for the long-lived overpack container for TRU wastes.

The repository cost estimates for each waste treatment alternative are shown in Table 8.9. A comparison of the total costs for the two cases shows substantially higher costs for the co-emplacement alternative. This higher cost is primarily caused by the increased costs for the long-lived overpack containers. These cost differences become much less noticeable as the wastes receive more treatment and as waste volumes are reduced.

LLW disposal costs are based on the rates charged at the Barnwell Low-Level Radioactive Waste Disposal Facility. These charge rates were obtained from the staff at the disposal facility. LLW disposal costs consist of a basic disposal charge plus additional surcharges that depend upon the characteristics of the

TABLE 8.9. Life-Cycle Repository Costs for Each Waste Treatment Alternative

	Waste Treatment Alternative					
	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incineration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
Case 1 - Co-emplacement ($millions)						
Facilities	1,073	1,073	1,073	964	973	964
Mine Operations	738	701	701	701	701	703
Waste Operations	3,934	2,785	2,743	2,260	1,866	2,271
Total (rounded)	5,750	4,560	4,520	3,930	3,540	3,940
Case 2 - Separate TRU/HLW emplacement ($millions)						
Facilities	1,073	1,073	1,073	964	973	964
Mine Operations	885	783	786	739	718	736
Waste Operations	2,356	2,352	2,289	2,064	1,794	2,094
Total (rounded)	4,310	4,210	4,150	3,770	3,480	3,800

(a) Costs were calculated in mid-1984 dollars for disposal in a salt repository.
(b) Includes decommissioning costs.

waste. Additional surcharges are based on the waste's radiation level, weight, and curie content. Additional charges are also assessed for cask handling, high integrity containers (if required), state and county taxes, and any special handling that may be required.

The disposal costs were calculated for the amounts of LLW expected to be generated from reprocessing 70,000 MTU of spent fuel. Annual LLW generation rates were presented for each waste treatment alternative in Section 6.0, including an estimated breakdown of the quantities of LLW-A, LLW-B, and LLW-C. The results of the LLW disposal cost calculations are presented in Table 8.10. As shown, the burial charges, which are based on unit volumes, are highest for the PWOT alternative and decrease as more treatment is applied to the waste. The costs for the high integrity containers follow the same patterns because the reduction in waste volumes reduces the number of containers needed. Costs for Alternatives 5a and 5b are higher than the costs for the other alternatives because they include disposal of contaminated zircalloy cladding material, which is disposed of in the geologic repository in the other alternatives. These wastes are still highly radioactive and thus incur substantial radiation and curie content surcharges as well as charges for high integrity containers. Additional charges for special handling of shipping casks for these materials are also assessed because of their radiation fields and shielding requirements.

8.4 WASTE MANAGEMENT SYSTEM COSTS

Total 70,000-MTU, life-cycle waste management system costs for each TRU waste treatment alternative are calculated in this section. Waste management system costs are the sum of waste treatment, transport, and disposal costs for each waste type that is produced in each alternative. Waste-treatment costs were calculated by adding together the capital and life-cycle operating costs. Life-cycle operating costs were calculated by multiplying the annual 1,500 MTU/yr-capacity operating costs times a conversion factor (70,000 MTU divided by 1,500 MTU/yr = 46.67 yrs). The results of these calculations are presented in Table 8.11. As shown, life-cycle waste treatment costs increase as the processing facilities become more and more complex. The life-cycle waste

TABLE 8.10. Life-Cycle Low-Level Waste Disposal Costs ($ millions) for Each Waste Treatment Alternative

	Waste Treatment Alternative					
Cost Category	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incineration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
Burial charge	78.9	41.4	33.1	25.3	42.9	43.4
Radiation surcharge	2.0	2.6	1.6	0.9	116.7	116.7
Weight surcharge	0.5	15.2	5.8	0.0	7.7	7.7
Curie surcharge	0.9	0.9	3.2	3.2	310.9	311.0
Cask handling	0.4	0.5	0.0	0.0	15.3	15.3
High Integ. Cont.	98.6	50.2	51.3	27.2	109.8	109.8
Taxes	38.2	20.5	16.3	12.3	31.5	31.8
Special handling	0.0	0.0	0.0	0.0	153.3	153.3
Total (rounded)	220.0	130.0	110.0	70.0	790.0	790.0

(a) Costs are given in mid-1984 dollars

TABLE 8.11. Life-Cycle Waste Treatment Costs for Each Alternative

	Waste Treatment Alternative					
	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incinceration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
Capital, $millions	227	259	276	299	316	316
Operating, $millions	1,008	1,157	1,419	1,419	1,512	1,512
Total, $millions	1,240	1,420	1,700	1,720	1,830	1,830

(a) Capital and operating costs are based on construction and operation of a 1,500 MTU/yr waste processing facility; costs are given in mid-1984 dollars.

treatment costs for Alternatives 2 through 5 range from 15 percent to 50 percent ($200 million to $600 million) higher than the life-cycle costs for the minimum treatment alternative.

Total life-cycle waste transportation costs are presented in Table 8.12 for each TRU waste treatment alternative. These costs were calculated by multiplying the unit transportation costs from Table 8.7 times the number of shipments of each waste type produced in each alternative from Table 8.8. As shown, total life-cycle transportation costs are highest for Alternative 1 (PWOT) and lowest for Alternative 4 (hulls melting). A reduction factor of about five, or over $1 billion, was calculated for Alternative 4 in relation to Alternative 1. The life-cycle trasportation costs for the PWOT alternative are about a factor of two ($800 million) more costly than the next highest alternative, Alterative 5a. Note that Alternative 5a, which has the highest TRU waste volume reduction, also has the lowest TRU waste transportation costs. However, this is more than offset by increased HLW transportation costs that result from adding TRUW into the HLW stream. Alternatives 5a and 5b also have the highest LLW transportation costs which cause this alternative to have higher transportation costs than Alternatives 2, 3, and 4.

Table 8.13 summarizes the total system cost estimates for each waste treatment alternative. These results are illustrated in Figure 8.1. Repository disposal costs account for approximately two-thirds of the total system costs followed in order of importance by waste treatment costs, transportation costs, and LLW disposal costs. The repository disposal costs are for the case in which HLW and TRU wastes are coemplaced in the same rooms and high-integrity overpacks are applied to the TRU waste containers. The treatment costs shown in the table increase from left to right as the treatment facilities become more complex to accomplish volume reductions and increase waste form stability. Transportation and disposal costs, on the other hand, decrease from left to right (except for Alternative 5) as waste volumes are reduced.

In general, the increased costs to treat wastes in the more complex alternatives are more than offset by reductions in transportation costs that

TABLE 8.12. Life-Cycle Transportation System Costs for Each Waste Treatment Alternative

	Waste Treatment Alternative					
Waste Type	1 PWOT	2 Compaction	3 Compaction + Incineration/ Cementation	4 Metals Melting + Incinceration/ Vitrification	5a Metals Decontamination + Incineration/ Vitrification to HLW	5b Metals Decontamination + Incineration/ Vitrification as TRUW
HLW, $millions	191	191	191	191	290	191
TRU waste, $millions	1,123	283	233	90	17	92
LLW, $millions	18	10	4	3	268	268
Total, $millions	1,330	480	430	260	580	550

(a) Costs are given in millions of mid-1984 dollars
(b) Shipments are assumed to travel 2,000 miles one-way
(c) Shipments are assumed to travel 300 miles one-way

TABLE 8.13. Total Waste Management System Costs ($ billions) for Each Alternative

	Waste Treatment Alternative					
	1	2	3	4	5a	5b
	PWOT	Compaction	Compaction + Incineration/ Cementation	Metals Melting + Incineration/ Vitrification	Metals Decontamination + Incineration/ Vitrification to HLW	Metals Decontamination + Incineration/ Vitrification as TRUW
Treatment Cost	1.24	1.42	1.70	1.72	1.83	1.83
Transport Cost	1.33	0.48	0.43	0.26	0.58	0.55
Disposal Cost						
HLW and TRUW	5.75	4.56	4.52	3.93	3.54	3.94
LLW	0.22	0.13	0.11	0.07	0.79	0.79
Total (rounded)	8.5	6.6	6.8	6.0	6.7	7.1

(a) All costs are given in billions of mid-1984 dollars

(b) Repository disposal costs are calculated for a bedded salt repository assuming co-emplacement and long-lived overpacks for all wastes

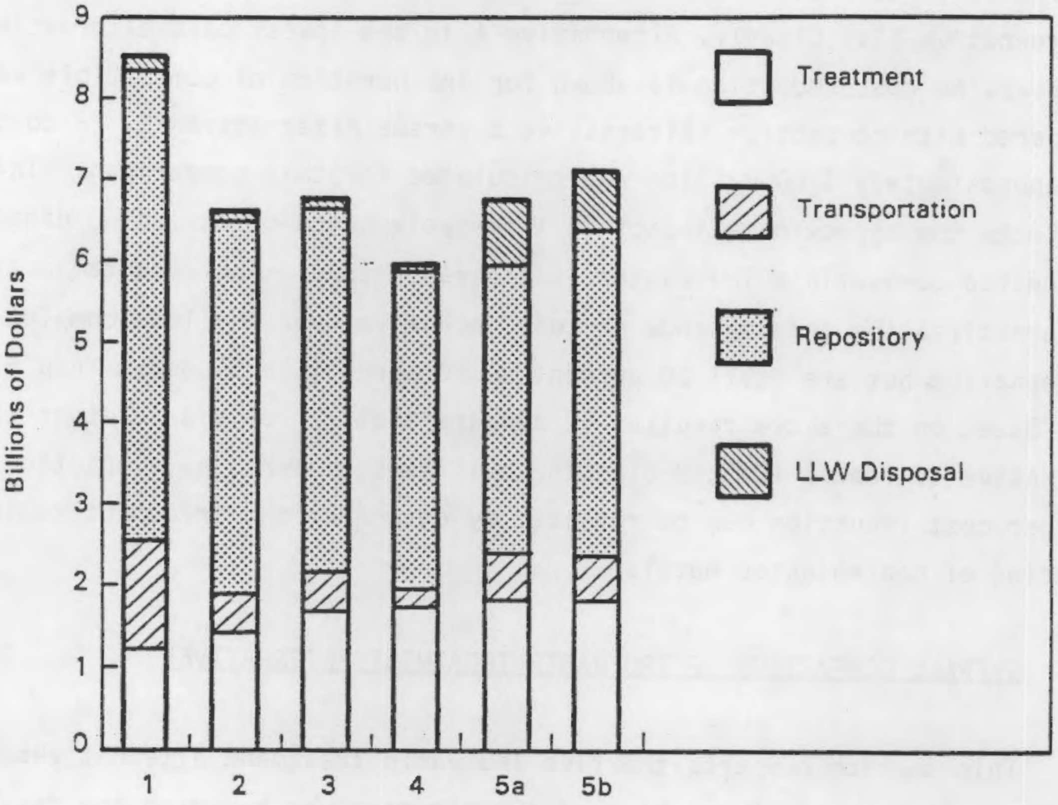

FIGURE 8.1. Life-Cycle Waste Management System Costs For Each TRU Waste Treatment Alternative

arise from volume reduction. A comparison of the total system costs for the treatment alternatives shows a significant cost reduction (about $2 billion) when the untreated wastes are compacted (Alternative 1 versus Alternative 2). A significant cost reduction ($2.5 billion) is also apparent when the Zircalloy cladding hulls and other contaminated metals are melted (Alternative 4) versus untreated (Alternative 1) or $0.8 billion when compared with compaction (Alternative 3). Clearly, Alternative 4 is the lowest cost alternative. However, no cost reduction is shown for incineration of combustible wastes when compared with compaction (Alternative 3 versus Alternative 2). A cost increase of approximately $200 million was calculated for this comparison. This increase reflects the approximate impact on life-cycle costs of excluding disposal of untreated combustible TRU wastes in the repository. The decontamination alternatives (5a and 5b) show no cost incentive over the less complex compaction alternative but are still 20 percent to 30 percent less costly than Alternative 1. Based on the above results, it appears that there is a substantial cost incentive to reduce TRU and cladding hull waste volumes by compaction. An even larger cost reduction can be realized by extending the treatment to include melting of contaminated metals.

8.5 OVERALL COMPARISON OF TRU WASTE TREATMENT ALTERNATIVES

This section compares the five TRU waste treatment alternatives and develops an approximate ranking of the alternatives based on the results of the near-term and long-term performance assessment and the life-cycle cost analysis. These results were used as evaluation parameters. The ranking of alternatives was done by first determining the most preferred alternative with respect to each evaluation parameter. The remaining alternatives were then ranked in order of preference (lower costs or higher performance) within each evaluation parameter. A value of 1 was assigned to the most preferred alternative, a value of 2 to the next best alternative, and so on, including ties, up to a maximum value of 6. The variable used as the primary ranking mechanism in this study was the total number of least preferred rankings for the waste treatment alternatives. The alternative ranked the lowest (i.e., least preferred and highest numerical rating) was that which was ranked the least preferred alternative with respest to the most evaluation parameters. Ties were decided by adding the ranking values for each alternative and then comparing the total values for the alternatives that are otherwise equal. The alternative with the lowest total value was ranked highest. Due to the uncertain nature of this ranking scheme, the results can only be considered to be approximate.

The results of the approximate ranking of TRU waste treatment alternatives are presented in Table 8.14. The most preferred alternative was determined to be Alternative 4, which includes hulls melting, compaction, and incineration capabilities. This alternative was not ranked "least preferred" with respect to any of the evaluation parameters and was the most preferred alternative with respect to long-term performance of the waste forms in the repository, near-term transportation risks, and life-cycle waste management system costs. Alternative 1 (PWOT) was the least preferred alternative because it was ranked "least-preferred" in three evaluation categories: long-term waste form performance, transportation risks, and life-cycle system costs.

Some additional comparisons were made to determine the effects on the waste management system of the various TRU waste treatment alternatives. First, Alternative 1 was ranked the lowest which indicates that TRU waste volume reduction will result in an overall improvement to the waste management system even though it may increase waste treatment costs and complexity and increase occupational risks. Based on the results of this study, the benefits of volume reduction (i.e., reduced repository and transportation costs and reduced transportation risks) outweigh the disadvantages previously mentioned. Furthermore, based on comparing Alternative 2 with Alternative 3, there is no apparent incentive for incinerating combustible TRU wastes. However, more detailed analyses are needed to compare the long-term performance of untreated combustible TRU waste forms with incinerated/cemented TRU waste forms. Based on the results presented here, the determining factor is the life-cycle system costs, which favor Alternative 2.

TABLE 8.14. Approximate Ranking of TRU Waste Treatment Alternatives

Evaluation Parameter	Waste Treatment Alternative 1 PWOT	 2 Compaction	 3 Compaction + Incineration/ Cementation	 4 Metals Melting + Incineration/ Vitrification	 5a Metals Decontamination + Incineration/ Vitrification to HLW	 5b Metals Decontamination + Incineration/ Vitrification as TRUW
Long-term performance of waste forms in repository,	4	4	4	1	2	2
Near-term performance						
- Routine proces- risks	1	2	3	4	5	5
- Risks from processing accidents	1	2	3	4	5	5
- Transportation risks	6	4	3	1	5	2
Life-cycle costs	6	2	4	1	3	5
Number of least-preferrable scores	3	1	1	0	2	2
Approximate overall ranking	6	2	3	1	4	4

(a) Rankings are based on a maximum range of 1 to 6, including ties, with respect to each evaluation parameter. Ties were broken by adding together the ranking values and comparing the totals.

Alternative 4 is the most preferred alternative primarily because of major reductions in the volume of hulls and hardware. In general, the alternatives are ranked from most preferred to least preferred in order of increasing volume of hulls and hardware. For example, Alternatives 2 and 3 are the next two highest ranked alternatives and also produce the second-lowest volume of hulls and hardware wastes. Alternatives 5a and 5b, which reduce a large portion of the hulls and hardware to LLW, are the next two highest-ranked alternatives. Finally, Alternative 1, which produces the highest volume of hulls and hardware, is ranked last. Thus, there is substantial incentive for reducing the maximum possible extent the volume of hulls and hardware wastes.

No incentive was determined for the hulls decontamination alternatives. These alternatives were ranked "least-preferred" in two evaluation categories; waste processing accident and routine risks. This was primarily due to the increased complexity of the waste processing facilities relative to the other alternatives. These are also relatively costly alternatives in comparison to Alternative 4. These two alternatives were ranked almost evenly, the principal differences being that Alternative 5a is less costly than 5b and 5b has lower transportation risks than Alternative 5a.

REFERENCES

AGNS. 1978. Studies and Research Concerning BNFP: Storage and Handling of Wastes from Uranium Fuel Processing Alternatives. AGNS-1040-3.3-34, Allied-General Nuclear Services, Barnwell, South Carolina.

Allen, R. P. 1982. "Development of Improved Technology for Decommissioning Operations." In Proceedings: 1982 International Decommissioning Symposium, Richland, Washington.

Anderson, K. J. and T. A. Evans. 1983. An Evaluation of General Process Trash Disposal by Compaction. ONI/3141/RD-03, Allied-General Nuclear Services, Barnwell, South Carolina.

Anderson, K. J. et al. 1982. BNFP Waste Characterization and Waste Treatment. PNL-3136-FR-01, Pacific Northwest Laboratory, Richland, Washington.

Anderson, K. J. et al. 1979. Studies and Research Concerning BNFP: Engineering Evaluations of Waste Handling Services and Storage Facilities. AGNS-35900-4.2-26. Allied-General Nuclear Services, Barnwell, South Carolina.

Atomics International (AI). 1973. Survey and Preliminary Evaluation of Shredding Equipment for Low Level Radioactive Waste. AI-73-42. Atomics International, Canoga Park, California.

Beauchamp, J. J. et al. 1983. The Statistical Sampling Plan for the TRU Waste Assay Facility. ORNL/CSD/TM-203, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Brodzinski, R. L. and N. A. Wogman. 1978. In Situ Quantitative Determination of Transuranic Elements in Areas of High Level Gamma Radiation. NBS Special Publication 528, National Bureau of Standards, Washington, D.C.

Buelt, J. L. and W. L. Partain. 1980. Safety Assessment of the Liquid Fed Ceramic Melter Process. PNL-3493, Pacific Northwest Laboratory, Richland, Washington.

Butcher, J. R., et al. 1980. Studies and Research Concerning BNFP: Report on Engineering Evaluation of Processing Alternatives. AGNS-35900-3.3-80. Allied-General Nuclear Service, Barnwell, South Carolina.

Caldwell, J. T., et al. 1983. Test and Evaluation of a High Sensitivity Assay System for Bulk Transuranic Waste. LA-UR-83-2084, Los Alamos National Laboratory, Los Alamos, New Mexico.

Caldwell, J. T. and W. E. Kunz. 1982. Experimental Evaluation of the Differential Dieaway Pulsed-Neutron Technique for the Fissile Assay of Hot Irradiated Fuel Waste. LA-UR-82-788, Los Alamos National Laboratory, Los Alamos, New Mexico.

Chambre, P. L. et al. 1982. Analytical Performance Models for Geological Repositories. LBL-14842, Lawrence Berkeley Laboratories, Berkeley, California.

Clark, L. L. et al. 1983. RECON: A Computer Program for Analyzing Repository Economics. PNL-4466, Pacific Northwest Laboratory, Richland, Washington.

Close, D. A., et al. 1983. Multi Isotopic Gamma Ray Assay System for Alpha Contaminated Wastes. LA-UR-83-1931, Los Alamos National Laboratory, Los Alamos, New Mexico.

Coplan, B. W. 1982. "Radwaste Incineration; Is it Ready for Use?" In Proceedings ANS Topical Meeting on the Treatment and Handling of Radioactive Wastes, American Nuclear Society, Richland, Washington.

Crane, T. W. 1980. Measurement of Uranium and Plutonium in Solid Waste by Passive Photon or Neutron Counting and Isotopic Neutron Source Interrogation. LA-8294-MS.

Daken, R. B. et al. 1973. Ceramic Electrode Heated Melter. BNWL-1809, Battelle Northwest Laboratories, Richland, Washington.

Darnell, G. R. and W. C. Aldrich. 1983. Low Speed Shredder and Waste Shreddability Tests. EEG-2226, Idaho National Engineering Laboratory, EG&G Idaho, Idaho Falls, Idaho.

Darr, D. G. 1983. Waste Model Characterization Study: Evaluation of Reprocessing Waste Estimates. AGNS, DOE/3156/FR-01, Allied-General Nuclear Services, Barnwell, South Carolina.

EG&G. 1982. Conceptual Design Report for SWEPP Support. Idaho National Engineering Laboratory, EG&G Idaho, Idaho Falls, Idaho.

Energy Research and Development Administration (ERDA). 1976a. Alternatives for Managing Wastes from Reactors and Post Fission Operations in the LWR Fuel Cycle. Vol. II, Section 12, ERDA-76-43, ERDA, Washington, D.C.

Energy Research and Development Administration (ERDA). 1976b. Alternatives for Managing Wastes from Reactors and Post Fission Operations in the LWR Fuel Cycle. Section: Treatment of Combustible Wastes. ERDA-76-43, ERDA, Washington, D.C.

Harada, M. et al. 1980. Migration of Radionuclides Through Sorbing Media Analytical Solutions-I. Lawrence Berkeley Laboratory, Berkeley, California.

Hedahl, T. G. 1982a. "Incinerator Development Program for Processing Transuranic Waste at the IdahoNational Engineering Laboratory." In Proc. ANS Topical Meeting on the Treatment and Handling of Radioactive Wastes, Richland, Washington.

Hedahl, T. G. 1982b. Controlled Air and Rotary Klin Incineration Proof of Practice Tests. EEG-WN-5841, Idaho National Engineering Laboratory, EGG Idaho, Idaho Falls, Idaho.

Klinger, L. M. 1983. Cyclone Incinerator - Operating Experience. MLM-3094, Mound National Laboratory, Miamisburg, Ohio.

Kunz, W. E. 1983. Differential Dieaway Technique Current Status of Los Alamos National Laboratory Work." In Proceedings of TRU Waste Assay Instrumentation Workshop, Los Alamos National Laboratory, Los Alamos, New Mexico.

Kunz, W. E., and J. T. Caldwell. 1982. Current Status of the Multi-Isotopic Transuranic Waste Assay System. LA-UR-82-787, Los Alamos National Laboratory, Los Alamos, New Mexico.

Kunz, W. E., et al. 1981. A 1 mg-Sensitivity Fissile Assay System. LA-UR-81-1358, Los Alamos National Laboratory, Los Alamos, New Mexico.

McCoy, M. W., et al. 1980a. Vibratory Finishing as a Decontamination Process. PNL-3336, Pacific Northwest Laboratory, Richland, Washington.

McCoy, M. W., et al. 1982b. Vibratory Finishing for Decontamination - Pilot Scale Operation. PNL-SA-9832, Pacific Northwest Laboratory.

Montgomery, D. R. and J. F. Nesbitt. 1983. Revue and Evaluation of Metallic TRU Nuclear Waste Consolidation Methods. PNL-4754, Pacific Northwest Laboratory, Richland, Washington.

Napier, B. A., W. E. Kennedy, Jr. and J. K. Soldat. 1980. PABLM - A Computer Program to Calculate Accumulated Radiation Dose from Radionuclides in the Environment. PNL-3209, Pacific Northwest Laboratory, Richland, Washington.

Neuhauser, K. S., J. W. Cashwell, P. C. Reardon, G. W. McNair. 1984. A Preliminary Cost and Risk Analysis for Transporting Spent Fuel and High-Level Wastes to Candidate Repository Sites. SAND84-1795, Sandia National Laboratories, Albuquerque, New Mexico.

Pattengill, M. G., et al. 1983. Incinerated Waste Consolidation Studies. EEG-2262, Idaho National Engineering Laboratory, Idaho Falls, Idaho.

Petrie, G. M. et al. 1983. Simplified Codes for Performance Evaluation (SCOPE) of Radionuclide Transport: Version 1.0. PNL-4737, Pacific Northwest Laboratory, Richland, Washington.

Postina, A. L. C. C. Chapman, and J. L. Buelt. 1980. An Assessment of Water/Glass Interactions in Waste Glass Melter Operations. PNL-2622, Pacific Northwest Laboratory, Richland, Washington.

Robinson, C. H. and C. J. Fry. 1981. "Steam Explosion Caused by the Contact of Molten Glass and Water." Proceedings of the International Seminar on Chemistry and Process Engineering for High-Level Liquid Waste Solidification, KFA Julich, Federal Republic of Germany.

Rogell, M. L. and P. D. Steneck. 1983. *Liquid Waste Solidification Facility - Detailed Design Criteria.* AGNS PNL/3154/RD-04, Allied-General Nuclear Services, Barnwell, South Carolina.

Ross, W. A., et al. 1982. *Comparative Assessment of TRU Waste Forms and Processes.* Vol. I - Waste Form and Process Evaluations. PNL-4428, Pacific Northwest Laboratory, Richland, Washington.

Schneider, V. W. and F. W. Ledebrink. 1982. "Treatment of TRU Wastes: Recent Results of Developments Underway in Germany." In *Proc. of ANS Topical Meeting on the Treatment and Handling of Radioactive Wastes*, American Nuclear Society, Richland, Washington.

Schultz, F. J. et al. 1983. *ORNL TRU Waste Assay System.* CONF-830660--1, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Slate, S. C., W. A. Ross, W. L. Partain. 1981. *Reference Commercial High-Level Waste Glass and Canister Definition.* PNL-3838, Battelle Pacific Northwest Laboratory, Richland, Washington.

Stearns-Rogers, 1983. *Cost Sensitivity Analysis - NWTS Repositories in Salt-Agmes Phase I Final Report*, Office of NWTS Integration (ONI) Battelle Project Management Division, Columbus, Ohio.

Strenge, D. L. et al. 1980. *ALLDOS - A Computer Program for Calculation of Radiation Doses from Airborne and Waterborne Releases.* PNL-3524, Pacific Northwest Laboratory, Richland, Washington.

Tenaglia, R. D. and J. L. McCall. 1983. *Induction Melting of Simulated Transuranic Waste.* EEG-2263. Idaho National Engineering Laboratory, EG&G Idaho, Idaho Falls, Idaho.

Walker, C. T. and U. Riege. 1979. "Compatability iof Actinides with HLW Borosilicate Glass: Solubility and Phase Formation." CONF790420. DOE Technical Information Center, Oak Ridge, Tennessee.

Wilmot, E. L. M. M. Madsen, and J. W. Cashwell. 1983. *A Preliminary Analysis of the Cost and Risk of Transporting Nuclear Waste to Potential Candidate Commercial Repository Sites.* Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Wogman, N. A., et al. 1978. *An Instrument for Monitoring the Transuranic Content of Chopped Leached Hulls from Spent Nuclear Fuel Elements.* NBS Special Publication 528, National Bureau of Standards, Washington, D.C.

U.S. Department of Energy (DOE). 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028, Department of Energy, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1983. Directory of Certificates of Compliance for Radioactive Materials Packages. NUREG-0384, Vol. 2, Rev. 5, Washington, D.C.

APPENDIX A

DETAILED DESCRIPTIONS OF WASTES TO BE TREATED AND FLOWSHEET BASES

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DETAILED DESCRIPTIONS OF WASTES TO BE TREATED AND FLOWSHEET BASES

A brief description of the reprocessing wastes to be treated was given in Section 3.0 and descriptions of the flowsheet bases used for the various waste treatment alternative processes were given in Section 5.0. More detailed information in these areas is presented in this appendix.

A.1 DETAILED DESCRIPTION OF WASTES TO BE TREATED

Table A.1 contains a summary of the waste stream data of Darr (1983), that are of most importance to this study. These waste streams were modified as described in Section 3.2. The data are grouped by waste type for ease in use when comparing waste treatment processes. The quantities of waste in each stream are given along with the classifications of the waste in each stream. Also given are some radionuclide contents and dose rates, which determine the waste classification. Treatment processes that change the waste volume or weight may change the classifications of some waste streams. Table A.1 allows the possible effect on each stream to be easily evaluated.

The data in Table A.1 provide the bases for the summary waste description tables in Section 3.3. For completeness, Tables 3.1, 3.3, and 3.4 are also presented here as Tables A.2, A.3, and A.4. The weights of various portions of the initial wastes are listed in a different format in Table A.5, where the wastes are grouped by waste type instead of by container size, as they were in Table A.4. The grouping in Table A.5 is more useful in studying different treatment options, as was done in this research.

Tables A.6, A.7, and A.8 contain summarized data on the radionuclide contents of different groupings of TRUW. Table A.6 compiles the quantities of Cs-137 and Pu-238 present in the CH and RH portions of the various waste types in the different containers. Table A.7 presents ratios of other fission product isotopes to Cs-137 and ratios of other actinide isotopes to Pu-238 in various waste grouping, thus allowing their quantities to be approximated for the groupings listed in Table A.6. Table A.8 is essentially the same as Table A.6, except that the radionuclide contents of the different waste groupings are presented as percentages of the total present in all of the TRUW groupings.

A.2 FLOWSHEET BASES

This section presents the bases used in developing information about the waste quantities present in each of the waste treatment alternatives studied.

A.2.1 Package Without Treatment-Alternative 1

In this alternative, the LLW and TRUW are assumed to be disposed of in the containers in which they are transported from the reprocessing facility. The total waste quantities are thus identical to the initial waste quantities that were described in Section 3.0 of this report.

The HLW glass resulting from vitrification of the liquid waste streams consists of 31 wt% of oxides of components of the HLLW and 69 wt% of the oxides that are added to form an appropriate glass. The glass quantity is 277 kg MTU (0.089 m^3/MTU). It is poured into canisters in 0.192 m^3 portions.

A.2.2 Compaction-Alternative 2

In the compaction alternative, most of the wastes are removed from the containers in which they arrive at the WTF and are then compacted within 160-gal canisters for disposal. Some of these wastes are shredded to reduce their size before they are compacted. Two types of waste, failed equipment and particulate solids, are not compacted. These wastes are disposed of in their original containers as in Alternative 1. HLW verification is identical to that in Alternative 1.

Waste volumes after compaction are based on estimated compaction factors (compaction factors used here are defined as the volume of the untreated, unpackaged waste divided by the volume of the compacted waste). A compaction factor of 3.33 was used here for hulls and hardware and a value of 4.0 was used for filters. For GPT, compactions factors of 4.0 and 1.67 were used for the combustible and noncombustible portions, respectively, giving an overall factor of 3.13 for the 80 percent combustible mixture which comprises the bulk of this waste. A compaction factor of 2.57 was used for SAC waste, which contains 60 percent combustible and 40 percent noncombustible material.

An in-can compaction process is used and wastes of different categories are assumed to be processed on a campaign basis with no cross contamination (no LLW is converted to TRUW during processing).

Compaction is performed in 22-in. diameter x 8-ft long (160 gal) carbon steel canisters. These canisters are assumed to be filled to 90 percent of their capacity during the compaction process.

Surface dose rates of the filled canisters were estimated by multiplying the initial surface dose rate by the initial packaged volume and dividing by the final package volume. This method of estimation assumes that compaction provides negligible additional shielding and that surface dose rate is affected little by package geometry.

A.2.3 Incineration/Cementation Plus Compaction-Alternative 3

In this treatment alternative, the wastes that contain organic material (the combustible GPT, the filters, and the SAC waste) are incinerated to destroy the organic material, and the incineration residues are immobilized with cement. Other wastes (hulls and hardware, noncombustible GPT) are compacted as in Alternative 2. Failed equipment remains untreated as in Alternatives 1 and 2 but particulate solids (other than those that are LLW-A) are cemented. HLW vitrification remains unchanged from that in Alternatives 1 and 2. The bases used to estimate the flowsheet values and the quantities of treated wastes are as follows:

1. The weight of incinerator ash is 3 percent of the weight of the materials actually burned (paper, rags, rubber, plastic, wood, filter adhesives).
2. The incinerator off-gas scrub concentrate volume is controlled by the chloride concentration and the concentrate contains 2.85 M chloride (chloride results from incineration of chlorinated plastics such as PVC). The combustible portions of the GPT and SAC wastes contain 10 wt% PVC, which contains 57 wt% chloride.

3. The wastes are incinerated on a campaign basis and the residues are segregated in the following categories:

   a. ash from GPT
   b. ash, media, and shredded metals from filters and SAC
   c. scrub concentrate from incineration of the LLW GPT
   d. scrub concentrate from incineration of other wastes.

4. The GPT ash is cemented using the formulation: 40 wt% ash, 32 wt% water, and 28 wt% cement. All of this material is TRUW.

5. The ash, media, and shredded metals from the filters and the SAC wastes are cemented using the formulation: 10 wt% filter media plus ash, 20 wt% water, 9.7 wt% shredded metals, and 60.3 wt% cement. All of this material is TRUW.

6. Excess scrub concentrate is cemented using the formulation: 35 wt% water and 65 wt% cement. This excess concentrate is part of that generated during incineration of the LLW GPT, so that the cemented product is LLW-A.

7. The scrub concentrate from the incinerator off-gas system is also used as the liquid in the cementation of the LLW-B and LLW-C and the TRUW particulate solids. The cement formulation used is: 50 wt% fluorinator solids, 22 wt% water, and 28 wt% cement. The scrub concentrate used for these LLW solids is part of that generated during incineration of the LLW GPT, so that the LLW portion of these wastes remains LLW.

8. Scrub concentrate was assumed to be used instead of water in all of the cement formulations. For simplicity, the density of the scrub concentrate solution was taken as 1.0 g/cm^3.

9. A density of 2.0 g/cm^3 was assumed for all of the cemented waste forms. A 90 percent fill factor was assumed in calculating the number of drums of cemented product.

10. The surface dose rates of drums containing the cemented products were approximated from the Cs-137 contents of the drums and the dose rate

per curie of contained Cs-137 calculated from the data in Darr (1983). A two-fold reduction in dose rate due to shielding by the cement was assumed.

11. The bases used for the wastes that are compacted in this alternative case (the hulls and hardware and the noncombustible GPT) are the same as those used for those wastes in Alternative 2.

A.2.4 Metals Melting Plus Incineration/Vitrification-Alternative 4

In this alternative treatment case, the metallic wastes are melted. The wastes that contain organic material are incinerated as in Alternative 3 but the nonmetallic solid incinerator residues are incorporated in the HLW glass instead of being cemented. The concentrated incinerator off-gas scrub solution and the particulate solids are immobilized by cementation as in Alternative 3.

The Zircaloy hulls and the stainless steel fuel hardware and other metallic wastes are melted into ingots that are estimated to be 90 percent of the theoretical density and that fill the 160-gal canister 90 percent full. Theoretical densities of 6520 and 7860 kg/m^3 were used for Zircaloy and stainless steel, respectively. Fuel hardware was estimated to account for 17.4 percent of the weight of the hulls and hardware (DOE 1979). No segregation is assumed for the melting operation, so that all metallic wastes become RH-TRUW.

The quantities of solid and liquid incineration residues in this case are the same as in the preceding case (Section A.2.3). The nonmetallic solid residues (incinerator ash and filter media) are added to the HLW vitrification process, with a corresponding reduction in the quantity of SiO_2 added in the glass-forming chemicals stream.

The cement formulations used for the mixed incinerator off-gas scrub concentrate plus particulate solids and for the excess scrub concentrate are the same as in the preceding case (Section A.2.3).

The dose rates of the cemented waste containers were estimated as in Alternative 3. All of the containers containing melted metals have very high dose rates, because no segregation of such wastes was assumed.

A.2.5 Metals Decontamination Plus Incineration/Vitrification-Alternatives 5A and 5B

In this alternative treatment case, most of the metallic wastes are decontaminated for disposal as LLW. The wastes that contain organic materials are incinerated with the nonmetallic solid incinerator residues being immobilized in glass. The concentrated incinerator off-gas scrub solution and some other wastes are immobilized by cementation. The secondary wastes resulting from metals decontamination are also immobilized in glass.

Two options were evaluated for this alternative. In the primary option (5a), the nonmetallic solid incinerator residues and the secondary wastes from decontamination are vitrified with the HLLW and ILLW so that HLW glass is the only vitrified product. In the secondary option (5b), these wastes are vitrified separately to produce a TRUW glass stream that also contains the particulate solids that are TRUW. Nondecontaminable metals are cemented in option 5a but melted in option 5b. Also in option 5b, the concentrated scrub solution that is TRUW is decontaminated to LLW before it is cemented, so that this option provides an example case where no cemented products need be placed in a repository.

The hulls decontamination process is estimated to remove (by abrasion) seven percent of the Zr and to use 9 g of Al_2O_3 abrasive per kg of hulls. The decontaminated hulls, which are cracked into smaller pieces prior to decontamination, have a bulk density of 1360 kg/m^3. These values are based on the results of preliminary development work at PNL. The ZrO_2 produced by oxidation of the Zr and the Al_2O_3 are incorporated in glass at loadings of 20 wt%. The density of this glass is 3000 kg/m^3.

The fuel hardware and other decontaminable metallic wastes are treated by vibratory finishing, which is estimated to remove 50 g (metal)/m^2 of surface and to use 350 g(Na in solution)/m^2 of surface. To estimate the surface area of the metals to be decontaminated, fuel hardware and failed equipment were assumed to have average thicknesses of 0.25 in. and the metals in GPT and SAC wastes were assumed to have an average thickness of 0.125 in. The bulk density of the decontaminated hardware is 1000 kg/m^3 (DOE 1979) and that of the other metals is taken to be twice as great as it was before treatment, because of better packing resulting from the size reduction that preceded decontamination. The Fe_2O_3 produced by oxidation of the removed iron is incorporated in glass at a loading of 33 wt%, and a glass density of 3000 kg/m^3.

These decontamination processes are estimated to reduce the contamination levels of TRU and other radionuclides by a factor of 10^3 to 10^4. They do not, of course, markedly reduce the content of neutron activation products that are present in the fuel hulls and hardware.

The decontaminated hulls and hardware are packaged in 160-gal containers that are within (or qualify as) high integrity containers for disposal. The other decontaminated metals are placed in 55-gal drums, and cement is added to form a monolith, except for the Class A wastes, which are not cemented.

A portion, estimated here at 30 percent of the total, of the failed equipment and noncombustible GPT wastes is not readily decontaminable. In option 5a these wastes are placed within 55-gal drums at the same bulk density as the untreated waste and cement is added to fill the void spaces. The volume of cement is estimated to be 25 gal/drum. In option 5b these wastes are melted and packaged using the same bases as established in the metals melting alternative (Section A.2.4).

Failed equipment that is LLW-A initially, and thus does not be decontaminated, is assumed to still undergo size reduction and be repackaged at bulk density twice as great as the initial value.

The shredded metals that passed through the incinerator are also treated differently in options 5a and 5b. They are cemented in option 5a and melted in option 5b, using the same bases as described in Sections A.2.3 and A.2.4, respectively.

The TRUW glass generated in option 5b also contains the TRUW fluorinator solids, which consist of 40 percent CaF_2 and 60 percent Al_2O_3 (DOE 1979). These solids are incorporated in the glass at loading of 20 wt% Al_2O_3; the weight of TRUW glass necessitated by this approach is 31 percent of the total.

Decontamination of the TRUW concentrated scrubber solution is accomplished by adding Fe(III) to a concentration of $1x10^{-3}\underline{M}$. The $Fe(OH)_3$ thus produced scavenges TRU elements from the solution, and aids in the removal of finely-divided TRU-containing solids, so that the solution will be LLW. This $Fe(OH)_3$ is also included in the TRUW glass at a 33 wt% loading.

A.3 APPENDIX A REFERENCES

Darr, D. G. 1983. Waste Model Characterization Study: Evaluation of Reprocessing Waste Estimates. AGNS, DOE/3156/FR-01, Allied-General Nuclear Services, Barnwell, South Carolina.

U.S. Department of Energy (DOE). 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028, Department of Energy, Washington, D.C.

TABLE A.1. Reprocessing Wastes to be Treated

Waste Type	Stream Number[(a)]	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU)		Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,[(b)] nCi/g	Waste Classification[(c)]
				m^3	kg				
Hulls and Hardware	21	300	600	637.13	486,000	1.7x10^{-4}	4.6x10^{6}	2x1^{4}	RH-TRUW
Filters (Metal Framed)	25B-1	51	80	5.10	663	2.8x10^{-6}	1.3x10^{2}	370	CH-TRUW
	-2	18	80	1.74	234	8.9x10^{-6}	4.1x10^{2}	1200	RH-TRUW
	-3	4	80	0.27	52	5.0x10^{-5}	2.3x10^{3}	300	RH-TRUW
	25C-1	3	600	1.08	135	1.7x10^{-3}	7.9x10^{4}	2x10^{5}	RH-TRUW
	-2	21	600	7.42	945	1.7x10^{-2}	7.9x10^{5}	2x10^{6}	RH-TRUW
	26A-1	14	80	1.42	182	6.3x10^{-9}	2.9x10^{-1}	1	LLW-A
	-2	2	80	0.20	26	7.0x10^{-7}	3.2x10^{1}	2	LLW-A
	26B-1	9	55	0.41	342	5.2x10^{-9}	7.7x10^{-1}	1	LLW-A
	-2	1	55	0.045	38	5.9x10^{-8}	8.8	8	LLW-A
	26C	8.5	80	0.85	110	7.0x10^{-7}	3.2x10^{1}	91	LLW-C
	45-1	33	80	1.87	429	2.8x10^{-6}	1.3x10^{2}	370	CH-TRUW
	-2	11	80	0.62	143	8.9x10^{-6}	4.1x10^{2}	1200	RH-TRUW
	46-1	50	80	2.83	650	6.3x10^{-9}	2.9x10^{-1}	1	LLW-A
	-2	6	80	0.34	78	7.0x10^{-7}	3.2x10^{1}	91	LLW-C
	52A-1	52	80	5.35	676	--	2.8x10^{-1}	5000	CH-TRUW
	-2	497	80	51.22	6,461	--	4.5	8x10^{4}	CH-TRUW
	-3	251	80	25.88	3,263	--	3.1x10^{1}	6x10^{5}	CH-TRUW

TABLE A.1. (contd)

Waste Type	Stream Number[a]	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU)		Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,[b] nCi/g	Waste Classification[c]
				m^3	kg				
Filters (Metal (Framed) (contd)	52B-1	1	55	0.085	38	--	2.7×10^{-1}	4200	CH-TRUW
	-2	19	55	1.61	722	--	3.5	6×10^{4}	CH-TRUW
	-3	30	55	2.55	1,140	--	1.7×10^{1}	3×10^{5}	CH-TRUW
	63A-1	2	600	0.85	90	1.7×10^{-3}	7.9×10^{4}	8×10^{4}	RH-TRUW
	-2	18	600	7.65	810	1.7×10^{-2}	7.9×10^{5}	8×10^{5}	RH-TRUW
	63B-1	77	80	8.72	1,001	2.8×10^{-6}	1.3×10^{2}	120	CH-TRUW
	-2	27	80	3.06	351	8.9×10^{-6}	4.1×10^{2}	380	RH-TRUW
	-3	9	80	1.02	117	5.0×10^{-5}	2.3×10^{3}	2200	RH-TRUW
	63C-1	7	80	0.79	91	2.9×10^{-6}	1.3×10^{2}	13	LLW-C
	-2	2	80	0.23	26	8.9×10^{-6}	4.1×10^{2}	13	LLW-C
	64A-1	5	80	0.57	65	6.3×10^{-9}	2.9×10^{-1}	<1	LLW-A
	-2	1	80	0.11	13	7.0×10^{-7}	3.2×10^{1}	13	LLW-C
	64B	13	80	1.47	169	7.0×10^{-7}	3.2×10^{1}	30	LLW-c
Filters (Wood (Framed)	12	15	80	2.55	195	6.3×10^{-9}	2.9×10^{-1}	1	LLW-A
	25A-1	15	80	1.56	195	2.8×10^{-6}	1.3×10^{2}	2	LLW-B
	-2	5	80	0.52	65	8.9×10^{-6}	4.1×10^{2}	2	LLW-B

TABLE A.1. (contd)

Waste Type	Stream Number[a]	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU)		Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,[b] nCi/g	Waste Classification[c]
				m^3	kg				
Filters (Wood (Framed) (contd)	258-1	153	80	15.23	1,989	$2.8X10^{-6}$	$1.3x10^2$	370	CH-TRU
	-2	52	80	5.21	676	$8.9x10^{-6}$	$4.1x10^2$	1200	RH-TRU
	-3	12	80	0.81	156	$5.0x10^{-5}$	$2.3x10^2$	300	RH-TRU
	26C	25.5	80	2.55	322	$7.0x10^{-7}$	$3.2x10^1$	91	LLW-C
FRSS GPT[d]	13-1	606	55	129.04	12,726	$2.4x10^{-8}$	2.2	2	LLW-A
	-2	19	55	4.05	399	$8.7x10^{-8}$	8.3	2	LLW-A
Segregated Combustible GPT[e]	27-1	128	55	27.18	2,688	$1.6x10^{-6}$	$1.5x10^2$	220	CH-TRU
	-2	48	55	10.19	1,008	$5.2x10^{-6}$	$4.8x10^2$	680	RH-TRU
	-3	42.4	55	9.00	890	$3.5x10^{-5}$	$3.2x10^3$	4500	RH-TRU
	28-1	1440	55	305.82	30,240	$5.3x10^{-9}$	$4.8x10^{-1}$	1	LLW-A
	-2	1680	55	356.79	35,280	$7.0x10^{-8}$	6.4	9	LLW-A
	-3	502	55	106.53	10,542	$4.3x10^{-7}$	$4.0x10^1$	56	LLW-C
	29	460	55	97.69	9,660	$5.3x10^{-9}$	$4.8x10^{-1}$	1	LLW-A
	47	136	55	28.32	2,856	$5.3x10^{-9}$	$4.8x10^{-1}$	7	LLW-A
	48	136	55	28.32	2,856	$5.3x10^{-9}$	$4.8x10^{-1}$	1	LLW-A
	53-1	94.4	55	17.58	1,982	--	$7.3x10^{-1}$	4300	CH-TRU
	-2	137.6	55	25.63	2,890	--	9.6	$6x10^4$	CH-TRU
	-3	72	55	13.42	1,512	--	$6.0x10^1$	$4x10^5$	CH-TRU

TABLE A.1. (contd)

Waste Type	Stream Number(a)	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU)		Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,(b) nCi/g	Waste Classification(c)
				m^3	kg				
Segregated Combustible GPT (contd)	65-1	96	55	18.12	2,016	1.6×10^{-6}	1.5×10^{2}	71	LLW-C
	-2	36	55	7.36	756	5.2×10^{-6}	4.8×10^{2}	220	RH-TRU
	-3	32	55	6.06	672	3.5×10^{-5}	3.2×10^{3}	1500	RH-TRU
	66-1	1800	55	382.28	37,800	5.3×10^{-9}	7.6×10^{-2}	<1	LLW-A
	-2	1260	55	263.35	26,460	7.0×10^{-8}	6.4	3	LLW-A
	-3	376	55	71.02	7,896	4.4×10^{-7}	4.0×10^{1}	13	LLW-C
Segregated Noncombustible GPT(e)	27-1	32	55	27.18	2,688	1.6×10^{-6}	1.5×10^{2}	220	CH-TRU
	-2	12	55	2.55	252	5.2×10^{-6}	4.8×10^{2}	680	RH-TRU
	-3	10.6	55	2.26	233	3.5×10^{-5}	3.2×10^{3}	4500	RH-TRU
	28-1	360	55	76.46	7,560	5.3×10^{-9}	4.8×10^{-1}	1	LLW-A
	-2	420	55	89.20	8,820	7.0×10^{-8}	6.4	9	LLW-A
	-3	125	55	26.62	2,625	4.3×10^{-7}	4.0×10^{1}	56	LLW-C
	29	115	55	24.41	2,415	5.3×10^{-9}	4.8×10^{-1}	1	LLW-A
	47	34	55	7.08	714	5.3×10^{-9}	4.8×10^{-1}	7	LLW-A
	48	34	55	7.08	714	5.3×10^{-9}	4.8×10^{-1}	1	LLW-A
	53-1	23.6	55	4.39	496	--	7.3×10^{-1}	4300	CH-TRU
	-2	34.4	55	6.40	722	--	9.6	6×10^{4}	CH-TRU
	-3	18	55	3.34	378	--	6.0×10^{1}	4×10^{5}	CH-TRU

TABLE A.1. (contd)

Waste Type	Stream Number[(a)]	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU)		Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,[(b)] nCi/g	Waste Classification[(c)]
				m^3	kg				
Segregated Noncombustible GPT (contd)	65-1	24	55	4.53	504	1.6×10^{-6}	1.5×10^{2}	71	LLW-C
	-2	9	55	1.70	189	5.2×10^{-6}	4.8×10^{2}	220	RH-TRU
	-3	8	55	1.50	168	3.5×10^{-5}	3.2×10^{3}	1500	RH-TRU
	66-1	450	55	95.57	9,450	5.3×10^{-9}	7.6×10^{-2}	<1	LLW-A
	-2	315	55	65.84	6,615	7.0×10^{-8}	6.4	3	LLW-A
	-3	94	55	17.76	1,974	4.4×10^{-7}	4.0×10^{1}	13	LLW-C
Sample and Analytical Cell (SAC)	23-1	4	600	2.29	316	6.9×10^{-7}	5.3×10^{1}	89	LLW-C
	-2	21	600	12.06	1,659	3.4×10^{-6}	2.6×10^{2}	450	RH-TRU
	-3	7	600	4.02	553	6.1×10^{-6}	5.3×10^{2}	890	RH-TRU
	-4	2	600	1.16	158	1.0×10^{-4}	7.9×10^{3}	1.3×10^{4}	RH-TRU
	-5	2	600	1.16	158	1.0×10^{-3}	7.9×10^{4}	1.3×10^{5}	RH-TRU
	67-1	4	600	8.27	316	1.0×10^{-4}	7.9×10^{3}	4400	RH-TRU
	-2	1	600	2.07	79	1.0×10^{-3}	7.9×10^{4}	4×10^{4}	RH-TRU
Failed Equipment	11A-1	8	55	1.05	1,600	1.4×10^{-8}	5.8	2	LLW-A
	-2	17	55	2.21	3,400	8.6×10^{-8}	3.7×10^{1}	2	LLW-B
	11B-1	1	600	1.19	900	2.0×10^{-8}	8.6	2	LLW-A
	-2	1	600	1.19	900	1.2×10^{-7}	5.2×10^{1}	2	LLW-B

TABLE A.1 (contd)

Waste Type	Stream Number(a)	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU) m^3	Quantity of Contained Waste (per 1500 MTU) kg	Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,(b) nCi/g	Waste Classification(c)
Failed Equipment (contd)	24-1	5	600	7.08	4,500	3.6×10^{-8}	1.5×10^{1}	5	LLW-A
	-2	10	600	14.16	9,000	1.6×10^{-7}	6.9×10^{1}	21	LLW-C
	-3	2	600	2.83	1,800	6.0×10^{-7}	2.6×10^{2}	78	LLW-C
	-4	1	600	1.42	900	1.2×10^{-6}	5.2×10^{2}	160	RH-TRU
	-5	1	600	1.42	900	1.8×10^{-5}	7.7×10^{3}	2400	RH-TRU
	-6	1	600	1.42	900	1.8×10^{-4}	7.7×10^{4}	2.4×10^{4}	RH-TRU
	44-1	2	600	2.83	1,800	4.0×10^{-9}	1.7	1	LLW-A
	-2	8	600	11.33	7,200	3.6×10^{-8}	1.5×10^{1}	2	LLW-A
	51A-1	2	55	0.40	400	--	1.1×10^{-1}	680	CH-TRU
	-2	30	55	6.06	6,000	--	1.2	6800	CH-TRU
	-3	38	55	7.67	7,600	--	2.0×10^{1}	1.2×10^{5}	CH-TRU
	51B-1	1	600	1.42	900	--	3.8×10^{-1}	2600	CH-TRU
	-2	3	600	4.25	2,700	--	1.7	1.2×10^{4}	CH-TRU
	62-1	3	600	5.95	2,700	3.6×10^{-8}	1.5×10^{1}	2	LLW-A
	-2	5	600	9.91	4,500	1.6×10^{-7}	6.9×10^{1}	7	LLW-A
	-3	1	600	1.98	900	6.1×10^{-7}	2.6×10^{2}	26	LLW-C
	-4	1	600	1.98	900	1.8×10^{-5}	7.7×10^{3}	774	RH-TRU
Particulate Solids	41-1	46	55	8.66	15,318	2.0×10^{-7}	8.7×10^{1}	26	LLW-C
	-2	281	55	52.87	93,573	5.9×10^{-7}	2.6×10^{2}	77	LLW-C
	-3	93	55	17.50	30,969	2.0×10^{-6}	8.7×10^{2}	260	RH-TRU

TABLE A.1. (contd)

Waste Type	Stream Number[a]	Containers per 1500 MTU	Container Size, Gal	Quantity of Contained Waste (per 1500 MTU)		Sr-90 Content, Ci/g	Container Dose Rate, MR/hr	Effective TRU Content,[b] nCi/g	Waste Classification[c]
				m^3	kg				
Particulate Solids (contd)	42	35	55	6.60	11,655	$3.9\text{X}10^{-9}$	1.6	2	LLW-A
	43	4000	55	849.50	520,000	$2.1\text{X}10^{-9}$	$7.8\text{X}10^{-1}$	<1	LLW-A

(a) From Darr (1983).

(b) Effective TRU content is calculated to reflect in one value all of the transuranic activities pertinent to 10 CFR 61. It is the sum of the alpha-emitting transuranic elements with half-lives greater than 5 years plus 1/35 of the activity of Pu-241 plus 1/200 the activity of Cm-242. For the reference spent fuel of this study it is equal to 2.26 times the Pu-238 activity plus 1.02 times the Am-241 activity plus 1.00 times the Cm-244 activity.

(c) TRUW is that waste having an effective TRU content of 100 nCi/g or greater; that in containers having surface dose rates below 200 MR/hr is contact handled (CH), and that in containers having higher dose rates is remote handled (RH). The LLW classification, as given in 10 CFR 61, for most reprocessing wastes is determined by the TRU content, but the Sr-90 and Cs-137 contents are also sometimes important. LLW-A contains <10 nCi TRU/g, <0.04 Ci Sr-90/m^3, and <1 Ci Cs-137/m^3. LLW-B contains <10 nCi TRU/g, 0.04 to 150 Ci Sr-90/m^3, and 1 to 44 Ci Cs-137/m^3. LLW-C contains 10 to 100 nCi TRU/g, 150 to 7000 Ci Sr-90/m^3, and 44 to 4600 Ci Cs-137/m^3.

(d) FRSS GPT consists of 95% combustible and 5% noncombustible material.

(e) Division of GPT between combustible and noncombustible portions is as discussed in Section 3.0. It was also assumed that the radionuclide concentrations (Ci/g of waste) of the combustible and noncombustible portions of a waste stream are the same.

TABLE A.2. Initial Containers Per Year in Low-Level and TRU Waste Classes

		Drum/yr in Indicated Low-Level Waste Class			Drum/yr of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
Container Size and Waste Type	Stream Number[a]	A	B	C	<200	200-10^3	10^3-10^4	>10^4	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	625	--	--	--	--	--	--	625	--	--	625
- Segregated Combustible	27,28,29,47,48,53,65,66	6912	--	974	432	84	74.4	--	7,886	432	158.4	8,476
- Segregated Noncombustible	27,28,29,47,48,53,65,66	1728	--	243	108	21	18.6	--	1,971	108	39.6	2,119
- Total GPT									10,482	540	198	11,220
Failed Equipment	11A,51A	8	17	--	70	--	--	--	25	70	--	95
Particulate Solids	41,42,43	4035	--	327	--	93	--	--	4,362	--	93	4,455
Metal-Framed Filters	26B,52B	10	--	--	50	--	--	--	10	50	--	60
Total in 55-Gal Drums									14,379	660	291	15,830
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	15	20	25.5	153	52	12	--	60.5	153	64	277.5
Metal-Framed Filters	25B,26A,26C,45,46,52A,63B, 63C,64	71	9	28.5	961	56	13	--	108.5	961	69	1,138.5
Total in 80-Gal Drums									169	1,114	133	1,416
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	300	--	--	300	300
Failed Equipment	11B,24,44,51B,62	19	6	13	4	1	2	1	38	4	4	46
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	44	--	--	44	44
Sample and Analytical Cell (SAC) Waste	23,67	--	--	4	--	28	6	3	4	--	37	41
Total in 600-Gal Drums									42	4	385	431
Total All Drums									15,090	1,778	809	17,677

(a) Data and stream numbers are taken from Darr (1983) for reprocessing 1500 MTU/yr.

Note: (1) Container weights not included in defining TRU level.
(2) Wastes from iodine retention operations not included (78 55-gal drum/yr).
(3) Values may be converted to container/MTU by dividing by 1500.

TABLE A.3. Volume of Initial Wastes Before Containerization

Container Size and Waste Type	Stream Number[a]	m^3/MTU in Indicated Low-Level Waste Class			m^3/MTU of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
		A	B	C	<200	200-10^3	10^3-10^4	>10^4	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	0.0888	--	--	--	--	--	--	0.0888	--	--	0.0888
- Segregated Combustible	27,28,29,47,48,53,65,66	0.976	--	0.130	0.056	0.0113	0.0100	--	1.106	0.056	0.0214	1.183
- Segregated Noncombustible	27,28,29,47,48,53,65,66	0.244	--	0.0326	0.0140	0.00283	0.00251	--	0.276	0.0140	0.00534	0.296
- Total GPT									1.471	0.070	0.0267	1.568
Failed Equipment	11A,51A	0.00070	0.00147	--	0.00944	--	--	--	0.00217	0.00944	--	0.0166
Particulate Solids	41,42,43	0.571	--	0.0410	--	0.0117	--	--	0.612	--	0.0117	0.624
Metal-Framed Filters	26B,52B	0.00030	--	--	0.00283	--	--	--	0.00030	0.00283	--	0.0031
Total in 55-Gal Drums									2.092	0.0823	0.0384	2.212
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	0.00170	0.00138	0.00170	0.0102	0.00347	0.00054	--	0.00478	0.0102	0.00401	0.0190
Metal-Framed Filters	25B,26A,26C,45,46,52A 63B,63C,64	0.00334	0.0068	0.00128	0.0655	0.00363	0.00087	--	0.00531	0.0655	0.00449	0.0753
Total in 80-Gal Drums									0.0101	0.0757	0.0085	0.0943
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	0.425	--	--	0.425	0.425
Failed Equipment	11B,24,44,51B,62	0.0189	0.00740	0.0126	0.00378	0.00094	0.00227	0.00094	0.0389	0.00378	0.0042	0.0468
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	0.0113	--	--	0.0113	0.0113
Sample and Analytical Cell (SAC) Waste	23,67	--	--	0.00153	--	0.0107	0.00629	0.00215	0.00153	--	0.0191	0.0207
Total in 600-Gal Drums									0.0404	0.00378	0.460	0.504
Total All Wastes									2.1425	0.1618	0.507	2.810

(a) Data and stream numbers are taken from Darr (1983).

TABLE A.4. Weight of Unpackaged Initial Wastes

Container Size and Waste Type	Stream Number[(a)]	Kg/MTU in Indicated Low-Level Waste Class			Kg/MTU of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
		A	B	C	<200	200-10^3	10^3-10^4	>10^4	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	8.75	--	--	--	--	--	--	8.75	--	--	8.75
- Segregated Combustible	27,28,29,47,48,53,65,66	96.77	--	13.64	6.05	1.18	1.04	--	110.41	6.05	2.22	118.68
- Segregated Noncombustible	27,28,29,47,48,53,65,66	24.19	--	3.40	1.51	0.29	0.26	--	27.59	1.51	0.55	29.65
- Total GPT									146.75	7.56	2.77	157.08
Failed Equipment	11A,51A	1.07	2.27	--	9.33	--	--	--	3.34	9.33	--	12.67
Particulate Solids	41,42,43	354.44	--	72.59	--	20.65	--	--	427.03	--	20.65	447.68
Metal-Framed Filters	26B,52B	0.25	--	--	1.27	--	--	--	0.25	1.27	--	1.52
Total in 55-Gal Drums									577.37	18.16	23.42	618.95
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	0.130	0.173	0.221	1.326	0.451	0.104	--	0.524	1.326	0.555	2.405
Metal-Framed Filters	25B,26A,26C,45,46,52A 63B,63C,64	0.615	0.078	0.247	8.329	0.485	0.113	--	0.940	8.329	0.598	9.867
Total in 80-Gal Drums									1.464	9.655	1.153	12.272
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	324.0	--	--	324.0	324.0
Failed Equipment	11B,24,44,51B,62	11.40	3.60	7.80	2.40	0.60	1.20	0.60	22.80	2.40	2.40	27.60
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	1.32	--	--	1.32	1.32
Sample and Analytical Cell (SAC) Waste	23,67	--	--	0.211	--	1.475	0.316	0.158	0.211	--	1.949	2.16
Total in 600-Gal Drums									23.0	2.40	329.7	355.08
Total All Wastes									601.8	30.2	354.2	986.3

(a) Data and stream numbers are taken from Darr (1983).

TABLE A.5. Weight of Various Portions of Initial Wastes

		Kg/MTU in Indicated Low-Level Waste Class			Kg/MTU of TRU Waste in Indicated Dose Rate (mR/hr) Range(a)				Totals			
Waste Type	Waste	A	B	C	<200	$200-10^3$	10^3-10^4	$>10^4$	LLW	CH-TRU	RH-TRU	Total
Hulls and hardware	Hulls and hardware	--	--	--	--	--	--	324.0	--	--	324.0	324.0
Other compactible (but noncombustible) waste	Filter media(b)	0.332	0.0837	0.156	3.642	0.312	0.0723	0.440	0.572	3.642	0.824	5.038
	Metal filter frames(b)	0.288	0.026	0.0823	3.200	0.162	0.0377	0.440	0.396	3.200	0.640	4.236
Combustible (and compactable) waste	Wood filter frames(b)	0.0433	0.0577	0.0737	0.442	0.150	0.0347	--	0.175	0.442	0.185	0.802
	Filter adhesives	0.332	0.0837	0.156	3.642	0.312	0.0723	0.440	0.572	3.642	0.824	5.038
	GPT(c)	103.77	--	13.64	6.05	1.18	1.04	--	117.41	6.05	2.22	125.68
	SAC(d)	--	--	0.127	--	0.885	0.190	0.095	0.127	--	1.170	1.297
Poorly compactable (and noncombustible) waste	GPT(c)	25.94	--	3.40	1.51	0.29	0.26	--	29.34	1.51	0.55	31.40
	SAC(d)	--	--	0.084	--	0.590	0.126	0.063	0.084	--	0.779	0.863
	Failed equipment	12.47	5.87	7.80	11.73	0.60	1.20	0.60	26.14	11.73	2.40	40.27
Particulates	Fluorinator solids	--	--	72.59	--	20.65	--	--	72.59	--	20.65	93.24
	Fluorine generation solids	7.77	--	--	--	--	--	--	7.77	--	--	7.77
	Dryer solids	346.67	--	--	--	--	--	--	346.67	--	--	346.67

(a) As packaged in initial containers, and assuming that the dose rates of subdivided portions (e.g., filter media and frames) are the same.
(b) Filters are 33 wt% media, 33 wt% frames, and 33 wt% adhesives.
(c) GPT is 80% combustible.
(d) SAC is 60% combustible (PNL).

TABLE A.6. Quantities of Cs-137 and Pu-238 in Selected TRU Waste Groupings

		CH-TRU				RH-TRU			
			Ci/MTU				Ci/MTU		
Waste	Drum Size, Gal	Drum/MTU	Cs-137	Pu-238	Ratio Reference[a]	Drum/MTU	Cs-137	Pu-238	Ratio Reference[a]
Hulls and hardware	600	--	--	--	--	0.200	4.95×10^{2}	2.04×10^{0}	1,5
Filters	55	0.0333	--	1.02×10^{-2}	3	--	--	--	--
	80	0.7427	1.12×10^{-2}	6.87×10^{-1}	2,4	0.0887	2.81×10^{-2}	2.49×10^{-4}	2,5
	600	--	--	--	--	0.0293	3.00×10^{1}	4.18×10^{-1}	2,5
GPT	55	0.360	5.28×10^{-3}	2.54×10^{-1}	2,4	0.132	7.73×10^{-2}	1.15×10^{-3}	2,5
SAC	600	--	--	--	--	0.0247	2.96×10^{-1}	4.79×10^{-3}	2,5
Failed equipment	55	0.0467	--	2.70×10^{-1}	3	--	--	--	--
	600	0.0027	--	9.73×10^{-3}	3	0.0027	1.88×10^{-1}	4.55×10^{-3}	2,5
Fluorinator solids	55	--	--	--	--	0.0620	5.85×10^{-2}	1.56×10^{-3}	2,5
		1.18	1.65×10^{-2}	1.23		0.539	5.26×10^{2}	2.47	

(a) Refer to these columns in Table A.7 to obtain ratios to be used in calculating other radionuclide contents in the indicated waste portions.

TABLE A.7. Ratios of Other Radionuclides to Cs-137 and Pu-238 in Selected TRU Waste Groupings

	Ci/Ci Cs-137		Ci/Ci Pu-238		
Nuclide	Hulls and Hardware (1)	Other Waste[b] (2)	Some CH Waste (3)	Other CH Waste (4)	All RH Waste[c] (5)
H-3	3.2×10^{-1}	3×10^{-3}			
C-14	7.1×10^{-6}	5×10^{-6}			
Sr-90	1.1×10^{-1}	7×10^{-1}			
Zr-93	3.1×10^{-5}	2×10^{-5}			
Tc-99	2.4×10^{-4}	2×10^{-4}			
Cd-113M	1.1×10^{-5}	7×10^{-5}			
Sn-126	9.1×10^{-6}	6×10^{-6}			
I-129	4.3×10^{-7}	4×10^{-7}			
Cs-135	4.6×10^{-6}	5×10^{-6}			
Cs-137	1.00	1.00			
Sm-151	2.1×10^{-2}	2×10^{-2}			
Eu-152	9.0×10^{-5}	9×10^{-5}			
Eu-154	7.9×10^{-3}	8×10^{-3}			
Ra-226			--	5×10^{-14}	1.0×10^{-10}
U-234			--	2×10^{-7}	4.2×10^{-4}
Np-237			--	7×10^{-8}	1.4×10^{-4}
Pu-238			1.00	1.00	1.00
Pu-239			0.16	0.16	0.16
Pu-240			0.22	0.22	0.22
Pu-241			31	31	31
Pu-242			5.6×10^{-4}	5.6×10^{-4}	5.6×10^{-4}
Am-241			5×10^{-2}	5×10^{-2}	5.8×10^{-1}
Am-242M			3×10^{-4}	3×10^{-4}	3.6×10^{-3}
Am-243			6×10^{-4}	6×10^{-4}	6.7×10^{-3}
Cm-242			--	2×10^{-6}	3.0×10^{-3}
Cm-243			--	6×10^{-7}	1.1×10^{-3}
Cm-244			--	3×10^{-4}	5.8×10^{-1}

(a) From Oarr (1983), Appendix C, for fuel irradiated to 28,500 MWd/MTU and cooled 9 years.

(b) Values for individual streams may vary by 30% from the listed values.

(c) Values given are those for hulls and hardware. The values for the other groupings of Table 7a fall within a factor of two of these values (generally within ~30%). Some ratios vary up to a factor of 10^3 between drums.

TABLE A.8. Percentages of Cs-137 and Pu-238 in Selected TRU Waste Groupings

		CH-TRU			RH-TRU		
			% of TRUW Total[(a)]			% of TRUW Total[(a)]	
Waste	Container Size, Gal	Container/ MTU	Cs-137	Pu-238	Container/ MTU	Cs-137	Pu-238
Hulls and hardware	600	--	--	--	0.200	94.1	55.1
Filters	55	0.0333	--	0.28	--	--	--
	80	0.7427	0.002	18.6	0.0887	0.005	0.007
	600	--	--	--	0.0293	5.7	11.3
GPT	55	0.360	0.001	6.9	0.132	0.015	0.031
SAC	600	--	--	--	0.0247	0.056	0.13
Failed equipment	55	0.0467	--	7.3	--	--	--
	600	0.0027	--	0.26	0.0027	0.036	0.12
Fluorinator solids	55	--	--	--	0.0620	0.011	0.042
		1.18	0.003	33.3	0.539	100.0	66.7

(a) Total Cs-137 in TRUW = 526 Ci/MTU and total Pu-238 in TRUW = 3.70 Ci/MTU.

APPENDIX B

DETAILS OF FACILITY DESCRIPTIONS

APPENDIX B

DETAILS OF FACILITY DESCRIPTIONS

In Section 5.0, brief descriptions were given for the waste treatment facilities required to implement the five TRUW treatment alternatives. This appendix contains more detailed information, including plan and elevation drawings, for each of the five waste processing facilities (WPFs) considered in this study.

The WPF concept employed in this preconceptual engineering study is that of a facility or center that is removed and separate from the fuel reprocessing plant (FRP). This concept is similar to and much of the information and data used here were obtained from previous concepts and facilities designed to handle the solid and liquid wastes generated at BNFP (AGNS 1978, Anderson et al. 1979, Butcher et al. 1980).

The WPF is an integrated concept where the various waste treatment processes share some areas and they also share a common area, ventilation system, utilities, and services. As regulations, design criteria, and technology develop, changes will occur in the various processes, equipment, cell arrangements, and building layouts. However, the functional requirements and interactions of the various areas (i.e., hot cells, control room, etc.) are essential elements of a generic facility and changes in detail should not result in changes in cost that exceed the indicated accuracy of the current cost estimates.

B.1 DESCRIPTION OF WPF-1 (PACKAGE WITHOUT TREATMENT-ALTERNATIVE 1)

The waste treatment processes housed in WPF-1 are 1) HLLW and ILLW solidification (waste vitrification) and 2) waste assay, inspection, and certification. These separate processes will be described in more detail.

A general plot plan and arrangement for WPF-1 are shown in Figure B.1. Figures B.2 through B.5 provide floor plans for this facility at different

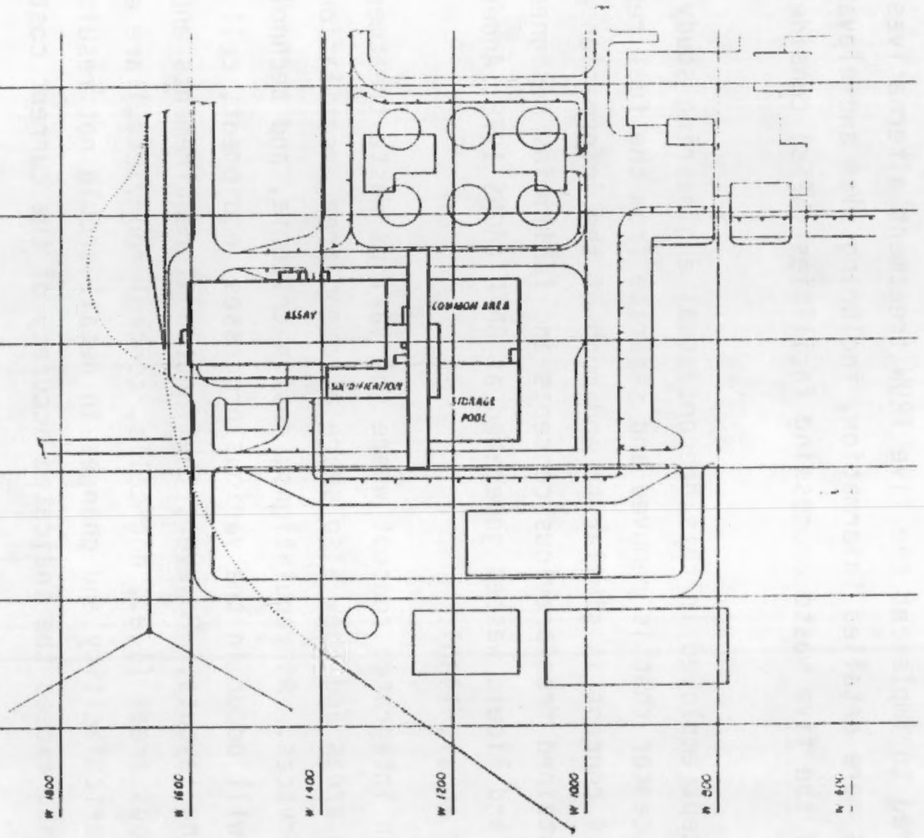


FIGURE B.1. General Plot Plan for WPF-1

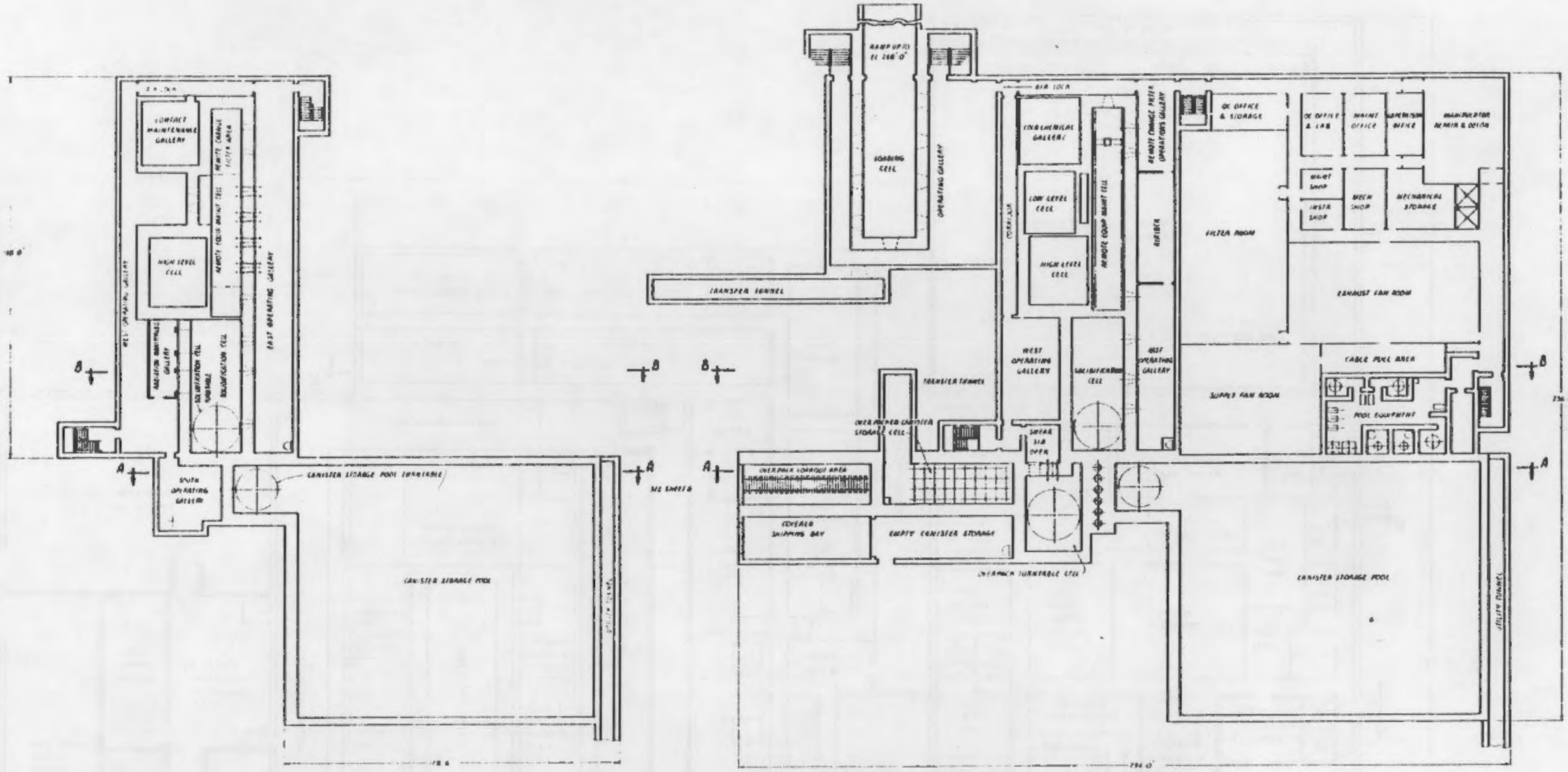


FIGURE B.2. Floor Plan for WPF-1, Elevations 236'-0" and 250'-0"

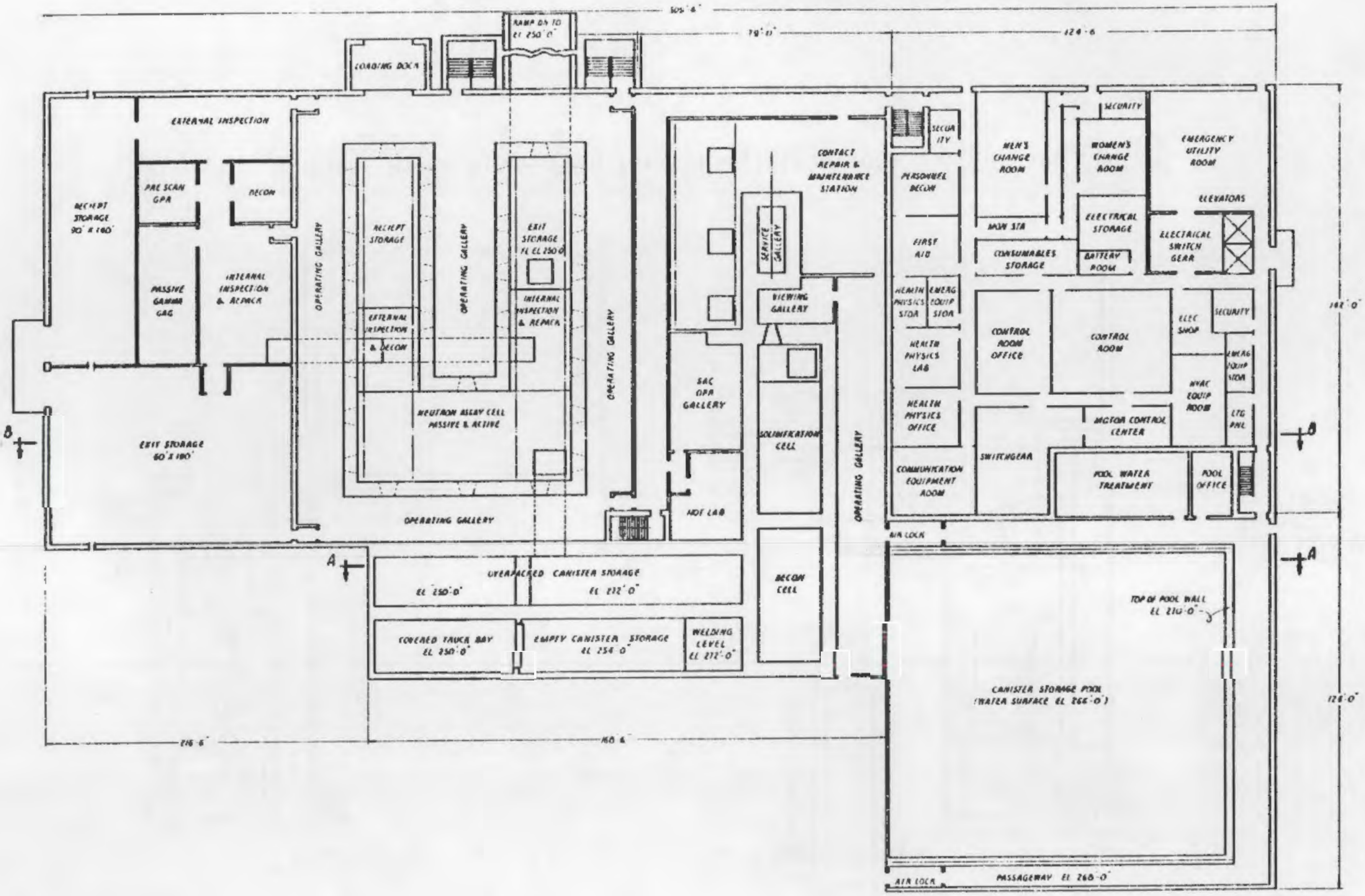


FIGURE B.3. Floor Plan for WPF-1, Elevation 268'-0"

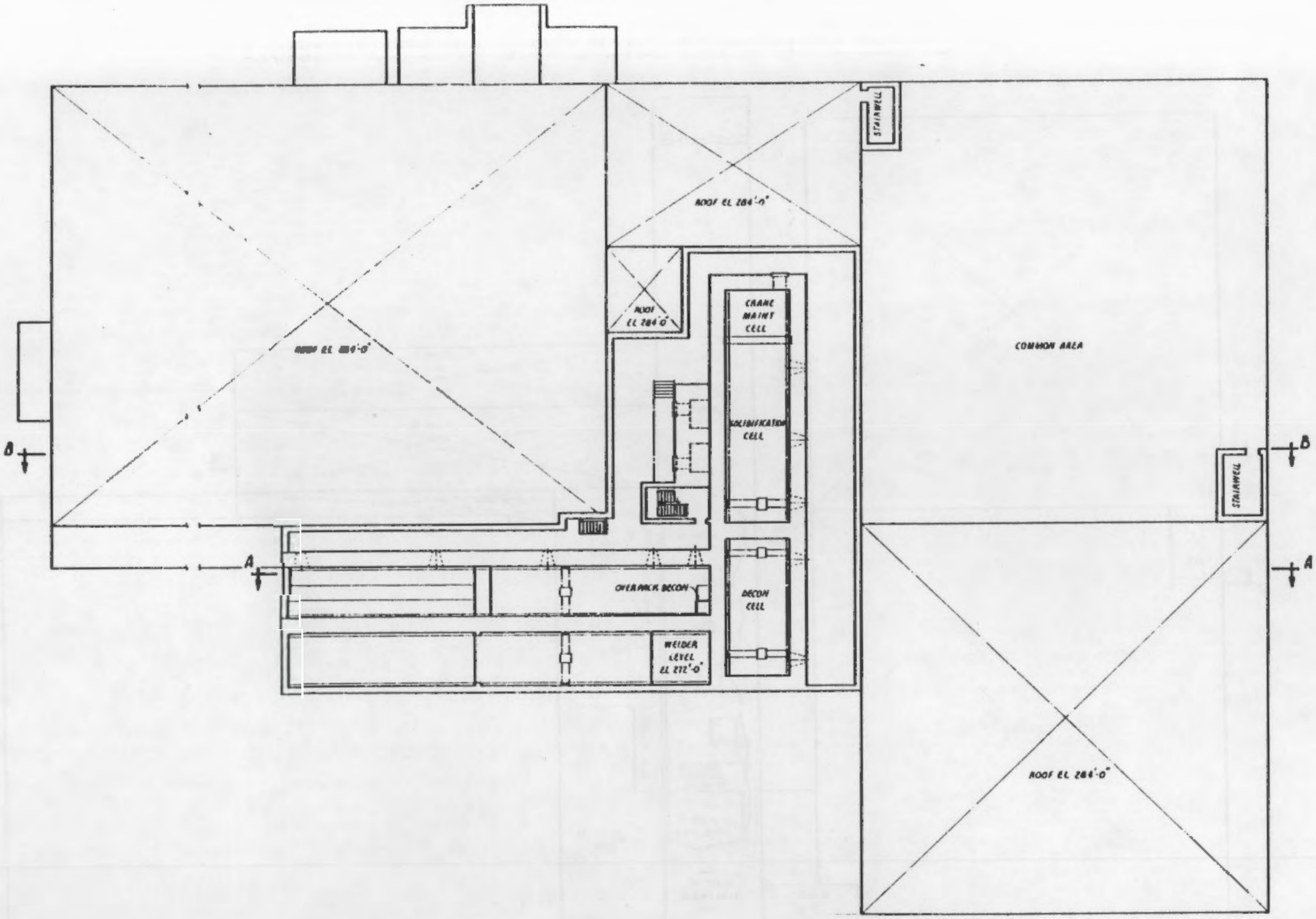


FIGURE B.4. Floor Plan for WPF-1, Elevation 284'-0"

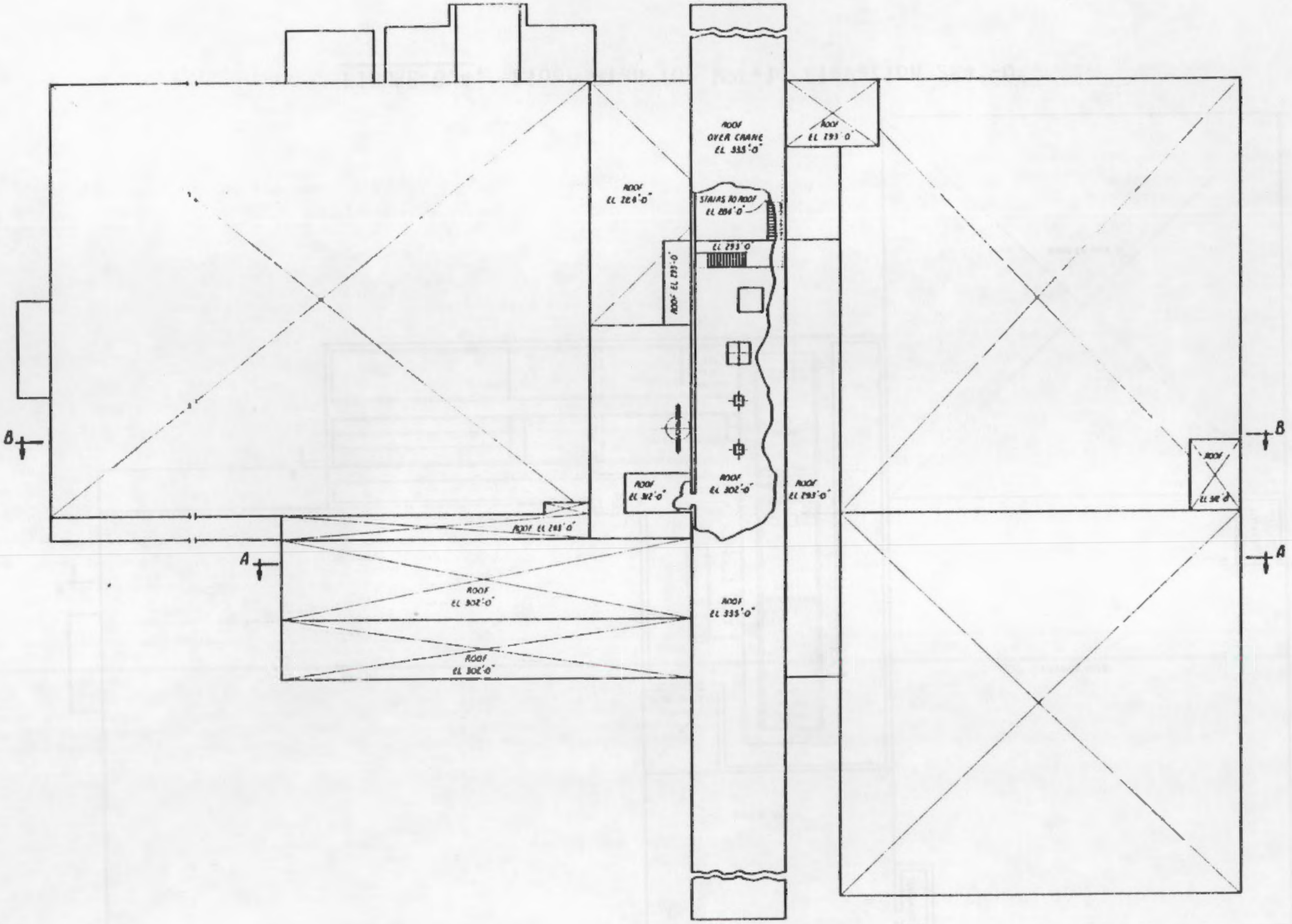


FIGURE B.5. Floor Plan for WPF-1, Elevation 335'-0"

elevations and Figure B.6 contains an elevation section that shows additional information on the vitrification cell and its associated and supporting facilities.

The total capital cost for WPF-1 is estimated to be about $227 million and the operating cost is roughly $21.6 million per year in 1983 dollar values.

B.1.1 Waste Vitrification (HLLW and ILLW)

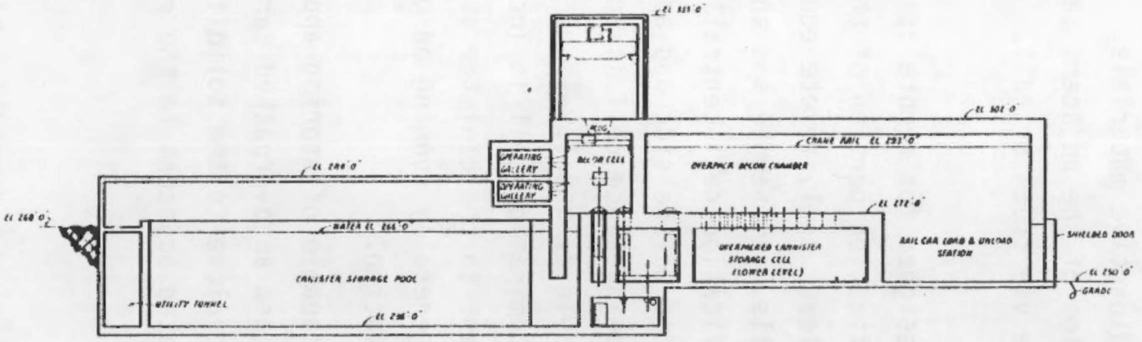
The waste vitrification portion of the WPF is divided into two functional areas: the process area and the canister storage area. The process area consists of hot cells for processing the highly radioactive materials, galleries for maintenance and remote manual operation of the adjacent cells, laboratories, and offices. Materials access can be via truck or rail. Loading bays are located at one side of the WPF.

The hot cells are personnel exclusion areas designed for remote operation and maintenance. The hot cells in the waste vitrification portion of the WPF are the solidification cell, high-level cell, low-level cell, remote equipment maintenance cell, decontamination cell, service cells, and sample and analytical cells. The cells are arranged with the solidification cell centrally located. The sample and analytical cells are located on one side and adjacent to the solidification cell. The remote equipment maintenance cell is located on one end of the solidification cell with the high-level and low-level cells along one side of the maintenance cell. The decontamination cell is located on the other end of the solidification cell and adjacent to the canister storage area. The cells have galleries adjacent to them, generally running on both sides of the cells, appropriately arranged for operation.

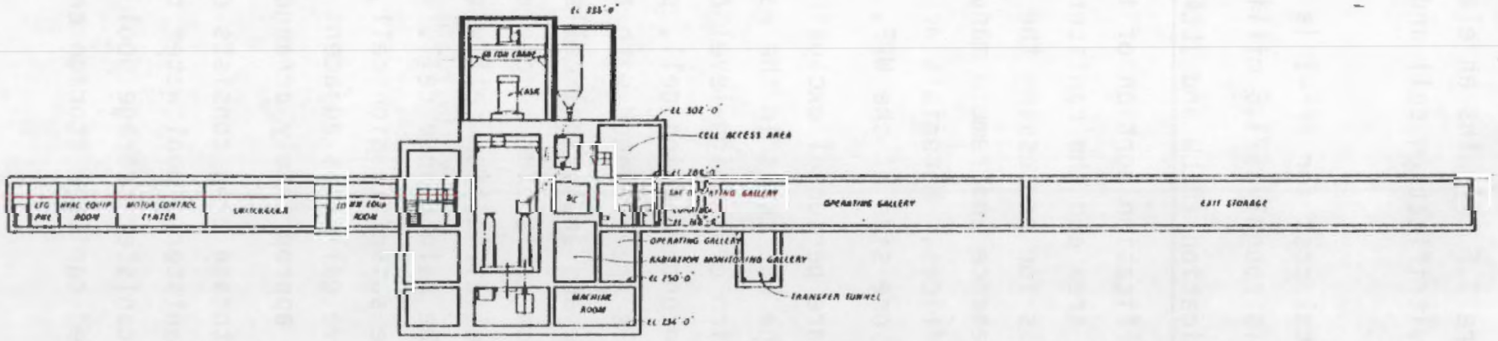
The canister storage area consists of a pool capable of storing approximately 1400 waste canisters, pool water treatment, and an overpacked canister storage cell. The canister storage pool is located close to the solidification cell. The overpacked canister storage cell is located adjacent to the railroad loading.

B.1.1.1 Waste Vitrification Facilities

The operations involved in waste vitrification are performed in shielded cells. Descriptions of these cells and their associated operating areas follow.



SECTION A-A



SECTION B-B

FIGURE B.6. Elevation of WPF-1 (Vitrification Cell

Solidification Cell

The ceramic melter solidification cell, where the liquid HLW is converted to borosilicate glass, is a reinforced concrete structure. Its walls are sufficiently thick to reduce the radiation dose rate at the outer wall to as-low-as-reasonably achievable (ALARA) levels (expected to be less than 100 mrem/hr in normally occupied areas). The cell is lined with stainless steel to assist in cell decontamination as well as eventual decommissioning. This lining will also protect the cell surfaces from corrosive chemicals and vapors. Plan views of the cell and the major equipment are shown in Figure B.7, and elevation sections are given in Figure B.8.

Some of the associated facilities of the operating galleries and services are also shown in the drawings noted above. Shielding windows are provided at various locations and levels for viewing and guiding the operations within the cell. There are penetrations for service equipment such as master-slave manipulators, periscopes, cell and process monitoring instrumentation, and facility operating equipment. Hot and cold service piping is encased in the walls and terminate at the in-cell remote connector heads.

Most cell equipment is modular in construction and these modules and/or the equipment are designed for remote removal, to facilitate maintenance and replacement. The overhead crane moves on rails built as part of the cell walls. Electrical-mechanical manipulator or radiation-resistant and decontaminable-robotic devices may also be arranged along the walls or on the floor of the cell.

The solidification cell contains two identical 100 percent capacity liquid-fed ceramic melter units with independent canister handling equipment. Normal canister access to and from the solidification cell is via the canister turntable. Empty canisters are transferred via the in-cell, 10-ton process crane to one of the ceramic melter turntables. These turntables are used for positioning canisters in either the load-in/load-out station or the glass-fill station. The empty canister is transferred to the canister load-in station and rotated to the glass-fill station located under the ceramic melter and lifted by the hydraulic-lift cylinder to contact the sealing surface of the

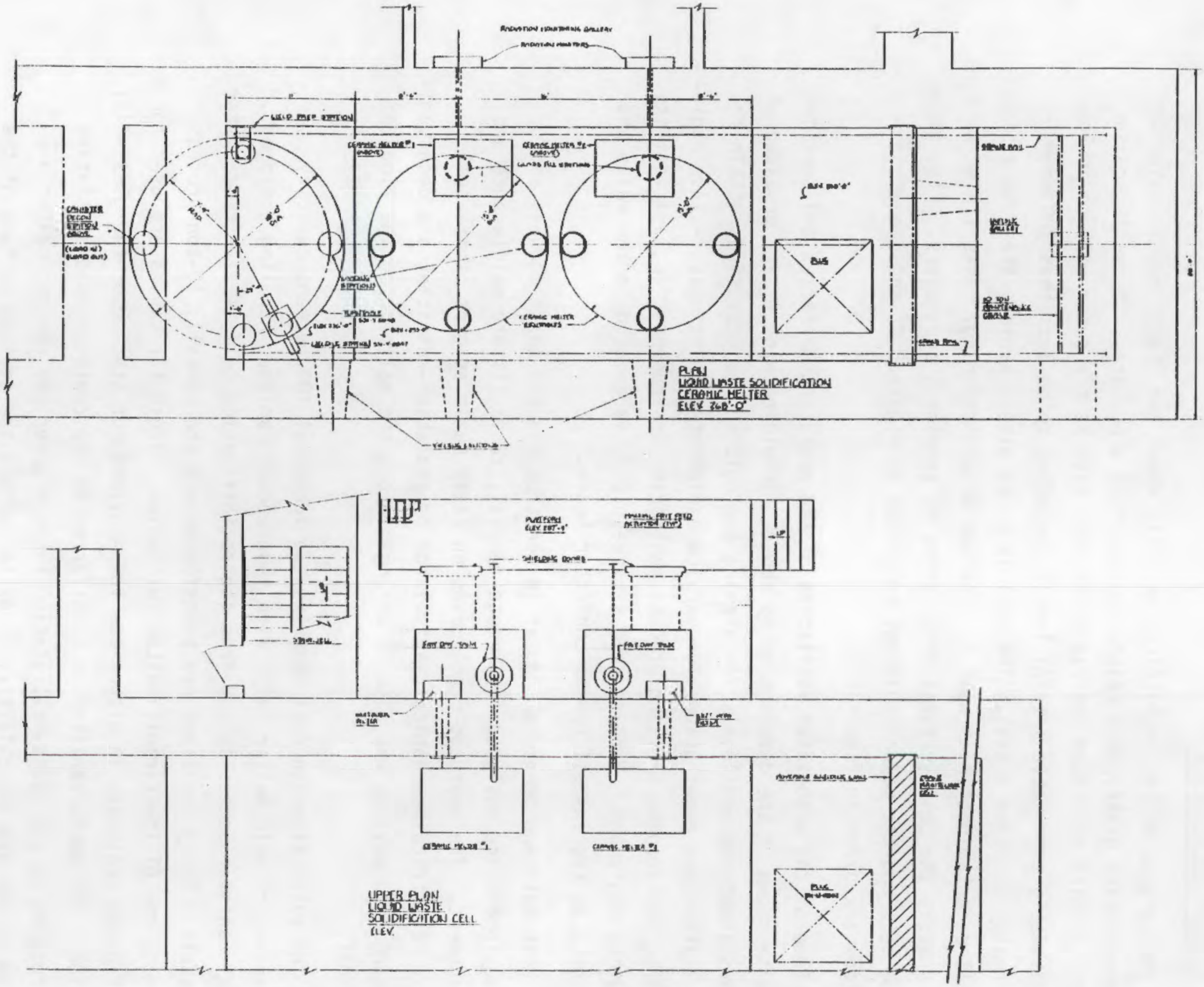


FIGURE B.7. Plan View of HLW Solidification Cell

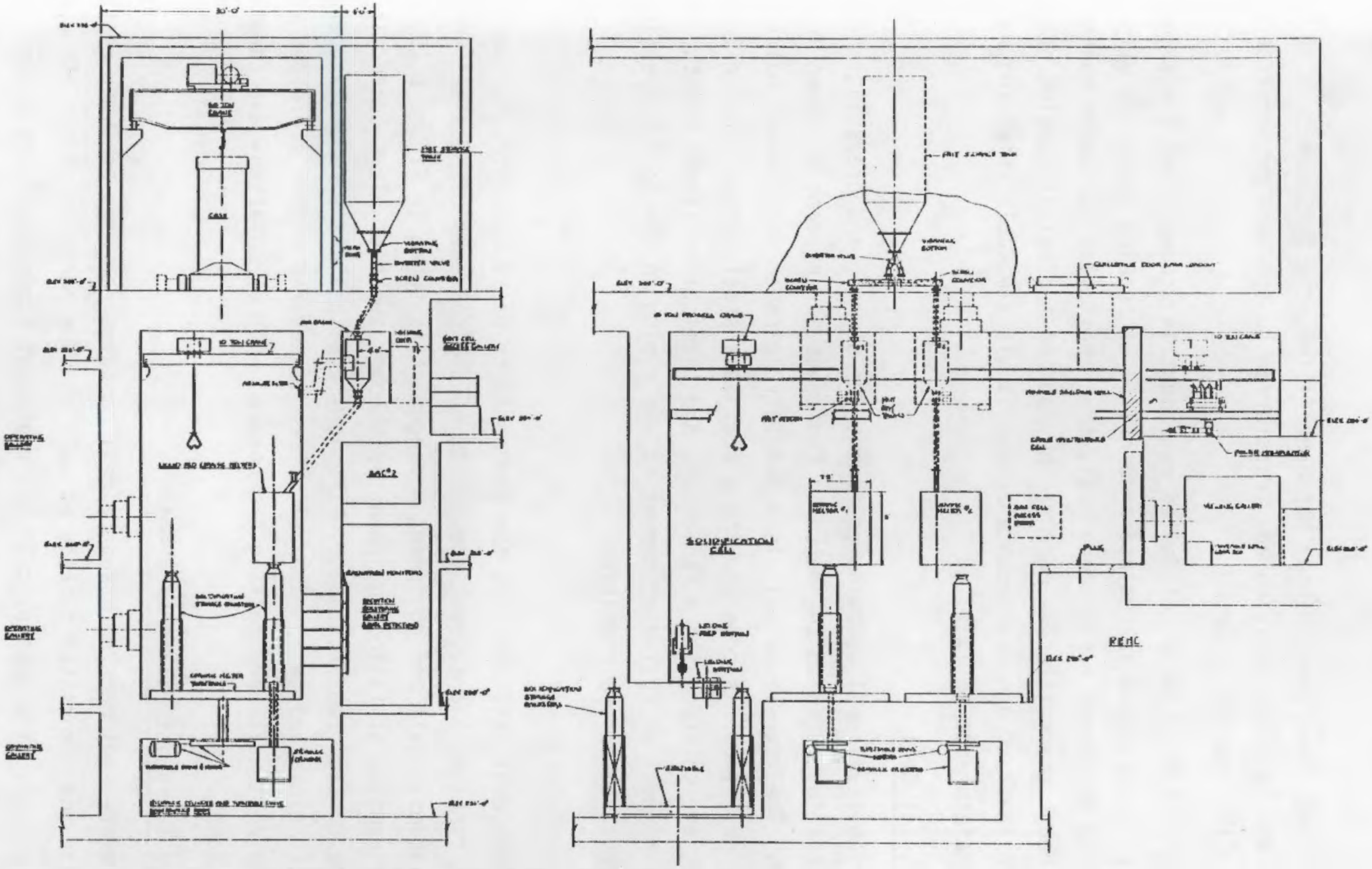


FIGURE B.8. Elevation Sections for HLW Solidification Cell ceramic melter. When the canister has been filled, the full canister is rotated to the load-out position and transferred to the weld preparation station via the process crane.

Cell access for removal of failed equipment is accomplished via a ceiling plug to the remote equipment maintenance cell. If repairs cannot be effected in the remote equipment maintenance cell, then the failed equipment can be removed through the guillotine door at the roof of the solidification cell to a cask on the roof. Crane maintenance access is via a movable shielding wall to the crane maintenance cell.

High-Level Cell

The high-level cell contains equipment for storing and preparing the liquid wastes to be fed to the melter. Equipment arrangement is shown in Figure B.9. The high-level cell is a remotely operated and contact maintained cell. The cell floor is covered with a stainless steel liner. The cell walls and ceiling are covered with a radiation- and chemical-resistant paint. Cell access for removal of failed equipment is via a plug in the roof connecting the cell to the contact repair station.

Low-Level Cell

The low-level cell contains the low activity waste concentration and associated tankage, and several components of the calciner off-gas and vessel off-gas systems. Cell and equipment arrangement is shown in Figure B.10. Cell access for removal of failed equipment is through two roof plugs connecting the cell to the contact repair station. The low-level cell is a remotely operated but contact maintained cell. The cell floor is covered with a stainless steel liner. The cell walls and ceiling are covered with a radiation- and chemical-resistant paint.

Remote Equipment Maintenance Cell

The remote equipment maintenance cell contains the high activity waste concentrator and associated tankage as well as some portions of the off-gas treatment system. The general cell and equipment arrangement are shown in Figure B.11. The remote equipment maintenance cell is a remotely operated and

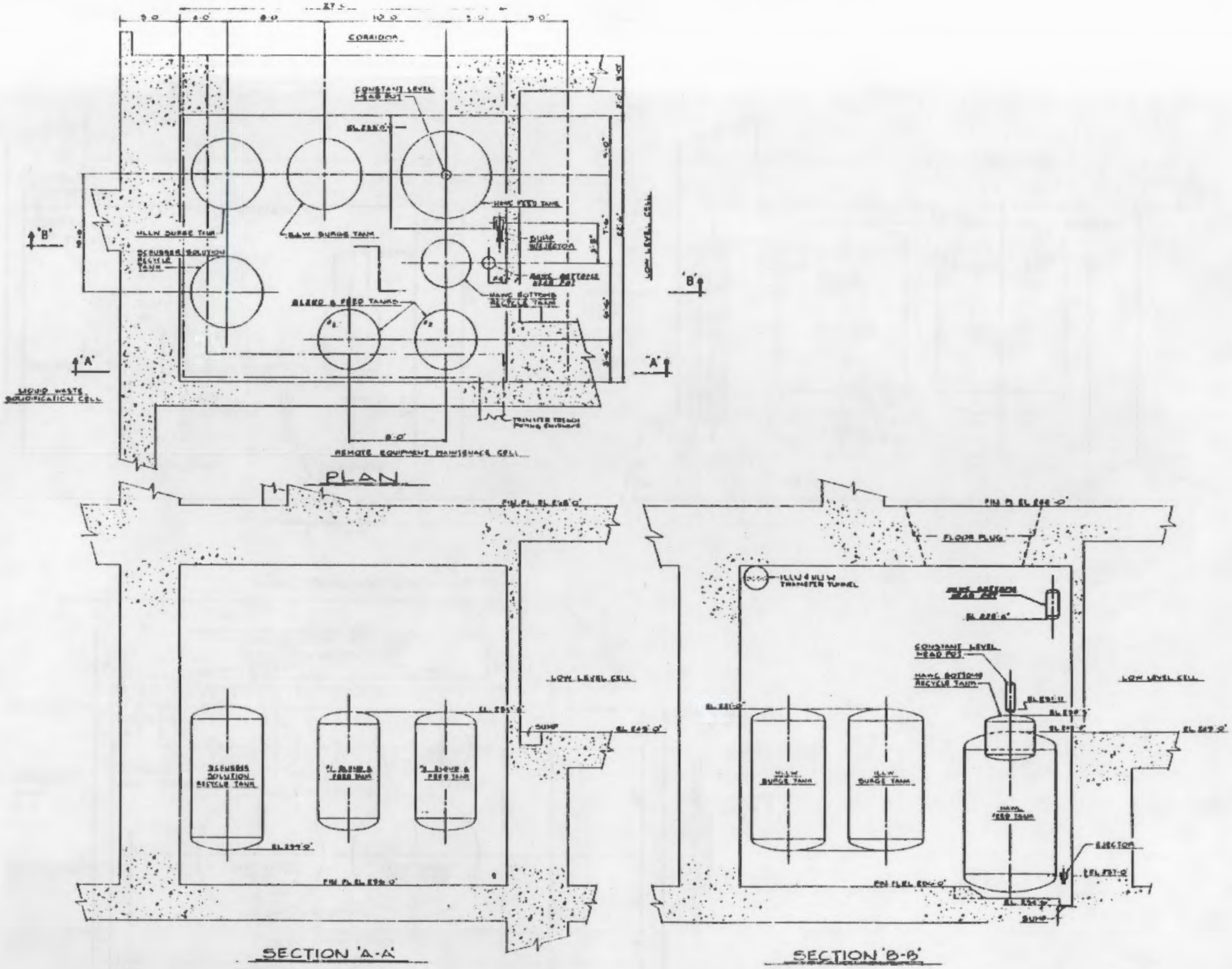
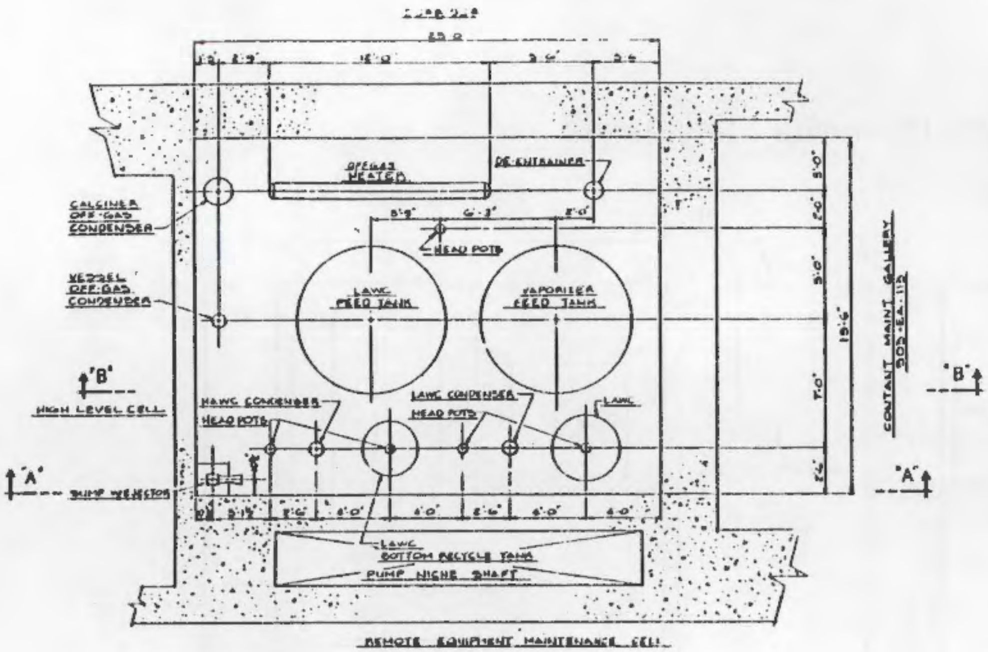
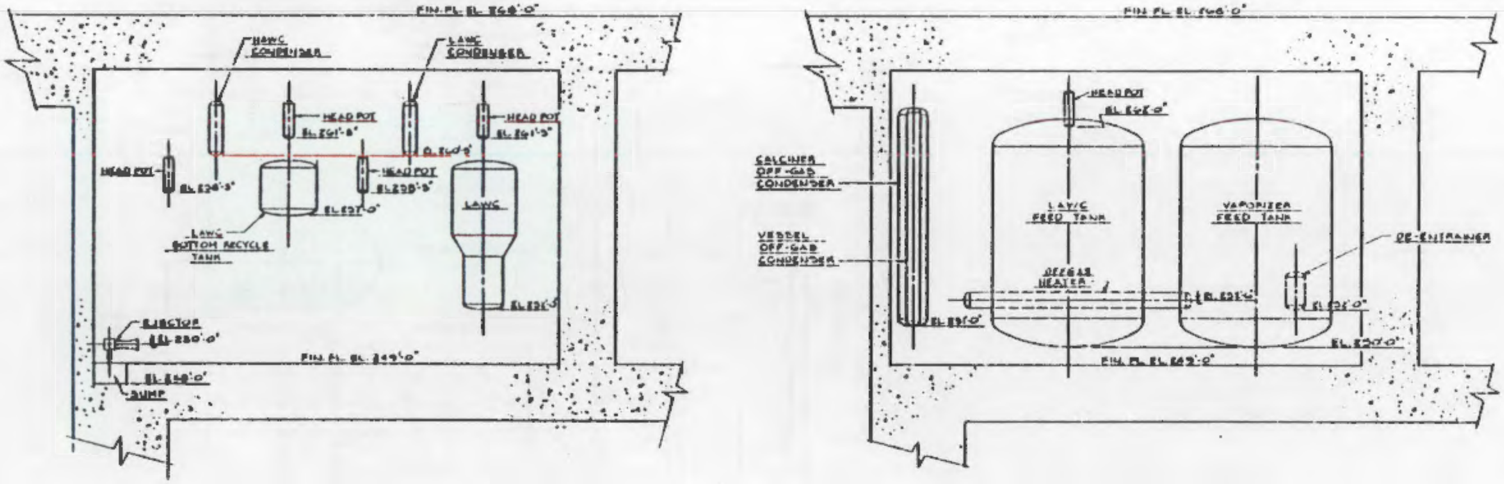


FIGURE B.9. High-Level Cell



PLAN



SECTION 'A-A'

SECTION 'B-B'

FIGURE B.10. Low-Level Cell

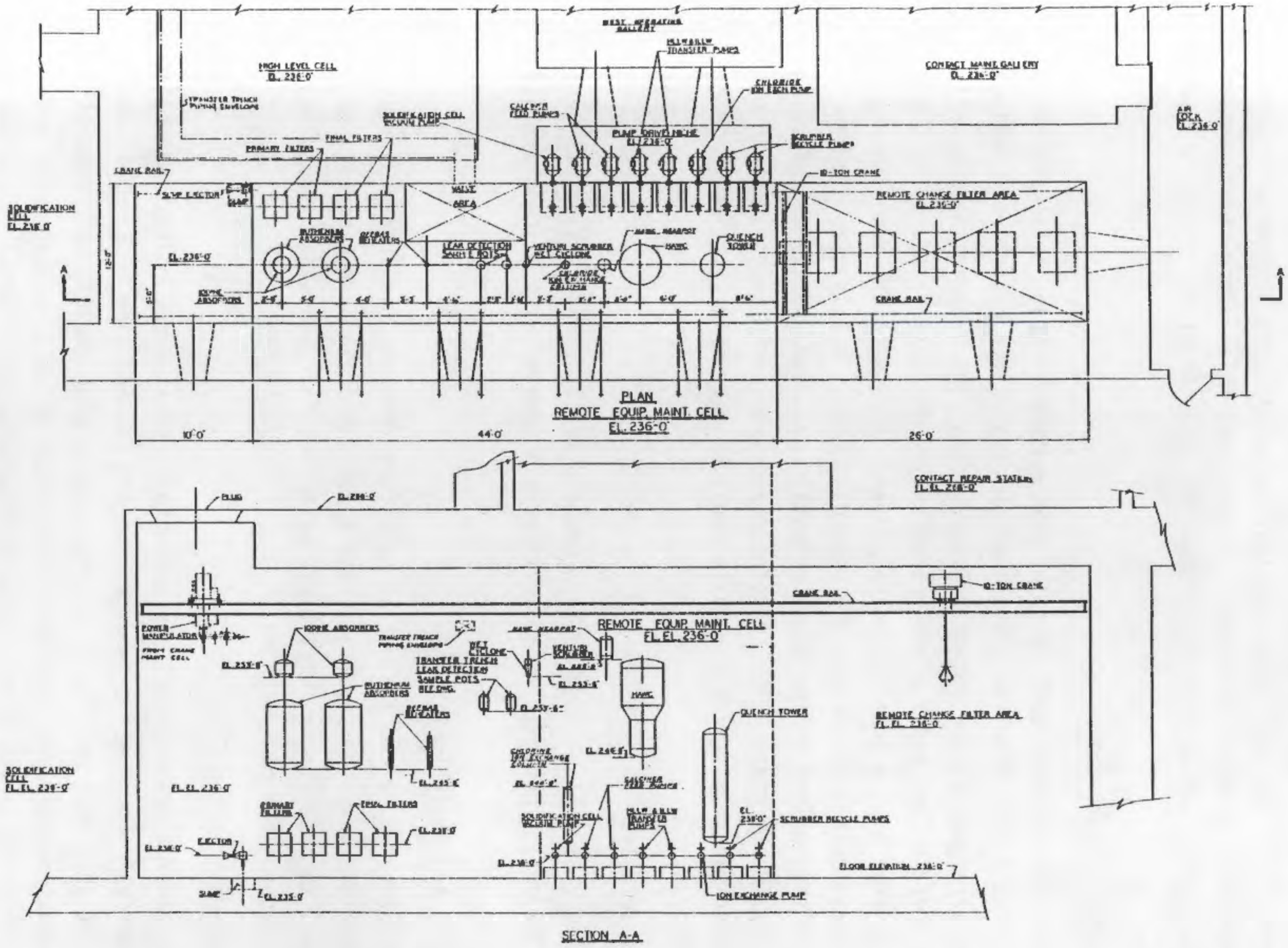


FIGURE B.11. Remote Equipment Maintenance Cell maintained cell. The cell floor, walls, and ceiling are covered with a stainless steel liner. Failed equipment, if not repairable in the remote equipment maintenance cell, can be removed through the solidification cell to a cask on the roof.

Decontamination Cell

The decontamination cell contains the equipment needed to remove radioactive contamination from the outside of the sealed HLW canisters. Cell and equipment arrangements are shown in Figure B.12. The decontamination cell is a remotely operated but contact maintained cell. The cell floor, walls and ceiling are covered with a stainless steel liner. Access to the decontamination cell for maintenance is through the shielding door. A shielding plug is located in the ceiling of the decontamination cell for removal of failed equipment by the 60-ton crane. The transfer drawers are used in conjunction with master-slave manipulators at the hulls canister and solidification canister smear stations.

Service Cells

The service cells are generally remotely operated but contact maintenance cells. The cell floor, walls, and ceiling are covered with a stainless steel liner.

Sample and Analytical Cells

The three sample and analytical cells are remotely operated and maintained cells which are used for sampling and analyzing the highly radioactive process solutions. Each sample and analytical cell contains a shielded window and a pair of master-slave manipulators.

Crane Maintenance Cell

The crane maintenance cell is a remotely operated but contact maintained cell. The cell floor, walls, and ceiling are covered with a stainless steel liner. The shielding wall is a 20.5 ft x 14 ft high movable wall separating the crane maintenance cell from the solidification cell, allowing the solidification cell crane access to the crane maintenance cell. After this crane is in the crane maintenance cell, the shielding wall can be raised to seal off the

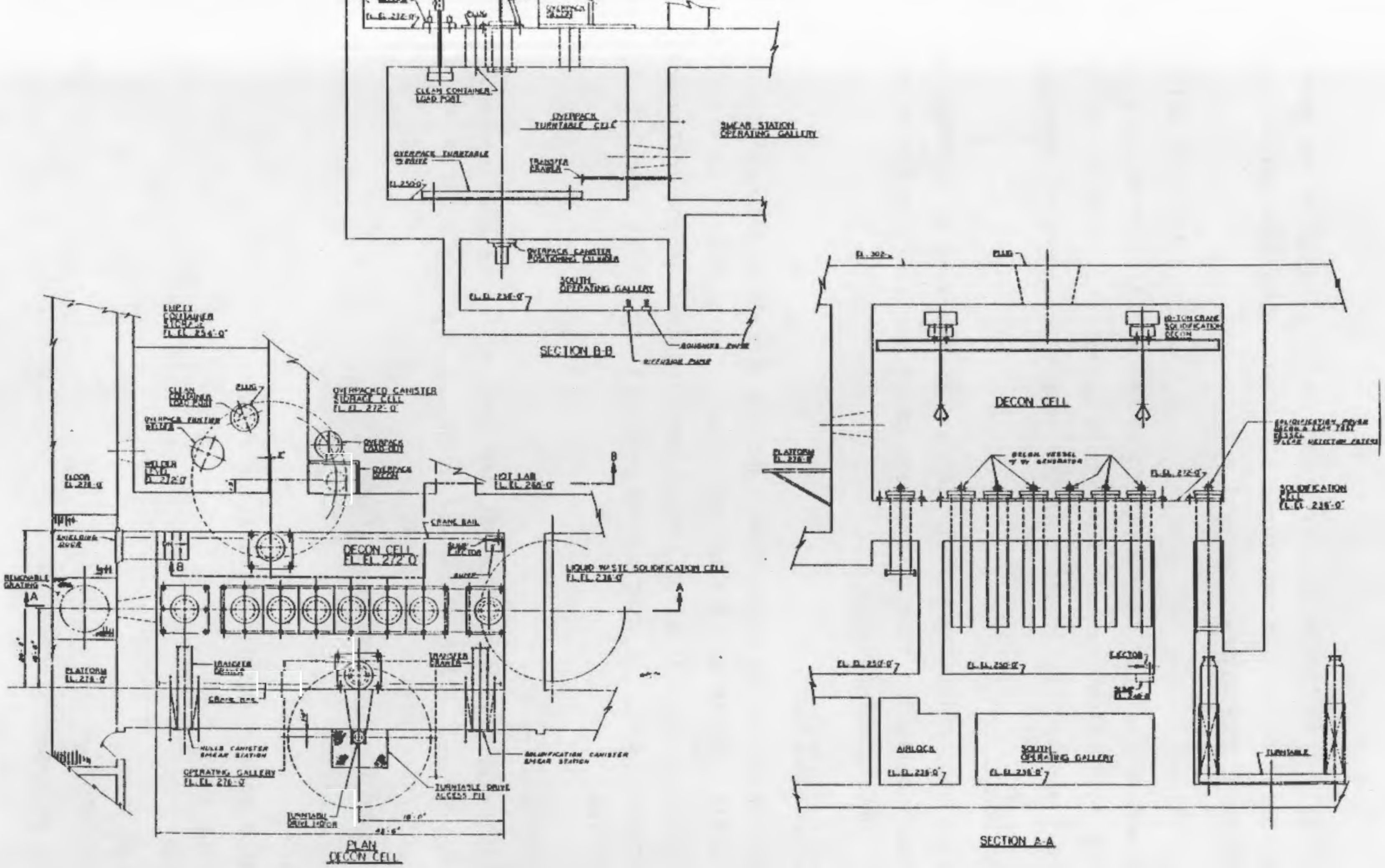


FIGURE B.12. Decontamination Cell

solidification cell from the crane maintenance cell. The crane can then be decontaminated prior to contact maintenance. A shielding door permits personnel entry into the crane maintenance cell.

The 10-ton crane is used for maintenance of the solidification cell crane. The power manipulator can be placed on the solidification cell crane and used in the solidification cell for remote operation. It can also be placed on a rail and trolley provided in the remote equipment maintenance cell.

Ancillary Cells

Other cells supporting the solidification process such as canister and container storage cells and turntable access cells are designed for remote operation and contact maintenance.

Operating Galleries

The operating galleries allow remote manual operation and maintenance of the adjacent cells. These operations are effected through cell penetrations from the galleries to the cells for remote handling devices and instrumentation. Most transmitters, jet gang valves, and utility piping are distributed in these galleries.

Process Support Area

The following process support areas are located in the WPF and serve the solidification process. These are shown in Figures B.2 and B.3.

- quality assurance office and storage
- quality control office and laboratory
- maintenance office
- supervisor's office
- manipulator repair and decontamination room
- maintenance shop
- instrument shop
- mechanical shop
- mechanical storage
- emergency equipment storage
- electrical cable pull
- security stations (3)

- personnel decontamination
- first aid
- health physics storage
- emergency equipment storage (2)
- health physics laboratory
- communications, telephone, and PA equipment room
- men's locker room
- women's locker room
- monitoring room
- consumable storage
- electrical storage
- battery room
- control room
- electrical shop
- lighting panel room
- motor control center
- switchgear room

B.1.1.2 Waste Vitrification Equipment

Some of the process and material handling equipment such as the liquid fed ceramic melter and turntables are among the equipment items that will require special design for the WPF. Other items such as canisters, canister welding equipment, and components of the off-gas system are typical of items for which existing designs can be modified and used in the WPF.

In-cell equipment is designed for simplicity of operation and maintenance. To aid in remote operations, all equipment is arranged to permit unobstructed crane access and is fitted with lifting devices (lugs, yokes, etc.). The use of equipment with moving parts that are subject to high maintenance frequency is minimized. All equipment is designed and selected on the basis of suitability for extended use and high reliability. Major pieces of process equipment are made of materials exhibiting high resistance to corrosion, radiation damage, and process operating conditions. Similarly, all of the equipment, piping, and instrument tubing in radioactive areas will be designed to withstand decontamination solutions and procedures.

The primary equipment for the ceramic melter process is shown in Figures B.7 and B.8. The major process equipment and estimated capacities are shown in Table B.1. Because of the preliminary nature of this design, no instrumentation is included and only approximate equipment capacities are given. The vessels will be constructed of an appropriate corrosion-resistant material commensurate with the process fluids, generally a 300-series stainless steel.

TABLE B.1. Major Process Equipment Characteristics

Equipment Description	Capacity
HLLW Surge Tank	8500 liters
ILLW Surge Tank	4252 liters
HLLW Pump	100 LPM
ILLW Pump	100 LPM
Blend and Feed Tank #1	5750 liters
Blend and Feed Tank #2	5750 liters
Liquid Fed Ceramic Melter	--
Quench Tower	550,000 Btu/hr
Venturi Scrubber	--
Wet Cyclone	--
Ceramic Melter Off-Gas Condenser	60,000 Btu/hr
De-entrainer	--
Scrubber Recycle Tank	9480 liters
Scrubber Recycle Pump	100 liters/minute
HAWC Feed Tank	1350 liters
HAW Concentrator	55 liters/minute
HAWC Bottoms Recycle Tank	1000 liters
HAWC Condenser	--
LAWC Feed tank	12,200 liters
LAW Concentrator	--
LAWC Bottoms Recycle Tank	120 liters
LAWC Condenser	--
Vaporizer Feed Tank	14,850 liters
Vaporizer	775,000 Btu/hr
Vessel Off-Gas Condenser	15,000 Btu/hr
Off-Gas Heater	15,000 Btu/hr
Primary Filters	--
Ruthenium Adsorbers	--
Iodine Adsorbers	--
Off-Gas Reheaters	--
Final Filters	--
Off-Gas Blowers	600 cfm
Off-Gas Heat Exchanger	--
Startup Heater	--
NO_x Destructor	--

Liquid-Fed Ceramic Melter

Depending upon the results of the waste form development effort, it may be necessary to operate the liquid fed ceramic melter at temperatures up to 1500°C to obtain acceptably leach-resistant and stable-waste glass. The melter is envisioned to have a center cavity lined with refractory brick to interface with and contain the pool of molten glass. The refractory brick is surrounded by insulating brick contained within a supporting structure of stainless steel.

Process heat is provided by high current density air-cooled electrodes. Additional heaters are placed around the molten glass airlift and overflow to prevent glass solidification before the glass reaches the canister. A sump is located in the bottom of the glass pool below the airlift to allow nearly complete removal of the molten glass. A freeze plug drain valve is located in the bottom of the melter glass drain. The feed and frit inlets, electrode connections, and off-gas outlet are contained in a removable top of the melter. The canister interfaces with the bottom of the melter below the molten glass port. A seal is required between the canister and the bottom of the melter to control off-gas flow into the cell.

HLW Canister

Figure B.13 shows the type of canister into which the melted glass is poured. After filling, the canister becomes the storage container for the waste glass. The design is conceptual for the purposes of this report (Slate, Ross, and Partain 1981). Actual waste canisters may be expected to differ in certain details.

The canister is 32 cm in diameter (12 in. schedule 40 pipe) and 3 m long. All canister materials are assumed to be 304L stainless steel. The size of the canister is determined primarily by constraints on decay heat loading, canister weight, and compatibility with transportation systems. From a solidification process standpoint, a 60 cm or even a 70 cm dia canister is attractive since their use would reduce the frequency of canister movement in the remotely operated process cell. However, the decay heat of typical commercial HLW is such that the heat generation rate of such a large canister may be too high for

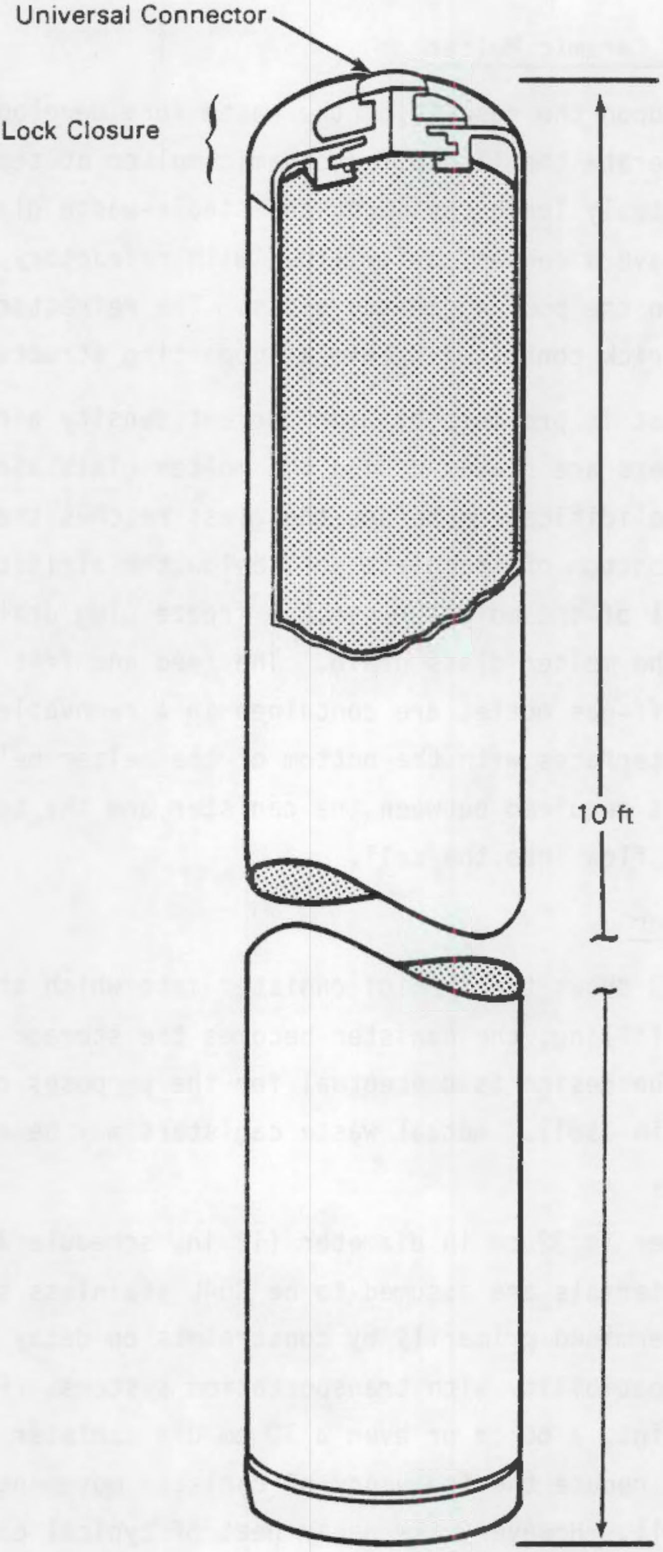


FIGURE B.13. Schematic of the Reference HLW Canister repository emplacement. Such HLW in a 32-cm diameter canister that is 3-m long will produce ~3.7 kW for HLW aged 5 years from reactor discharge and 2.2 kW when the HLW is aged to 10 years.

The canister-wall thickness is specified to be 0.64 cm (1/4 in.), which is much thicker than is required to meet the process-imposed stresses plus the corrosion allowances for both the inside and outside surfaces. However, the dimension is a prudent specification for impact and transportation protection.

The top of the canister is formed from a flanged-only tank head. The bottom is a slightly-reversed-dished flanged tank head. Stress analysis indicates the rounded corner and closure is less susceptible to impact damage than a simple flat-plate closure.

The actual lid closure at the top of the canister is a twist-lock fitting developed to permit a simple, airtight connection during filling that can be made with remote-handling equipment. The seal-weld surface is accessible for remote welding and can be checked for weld defects by ultrasonic scan. The weld leak check can be made with a helium detector.

B.1.1.3 Waste Vitrification Operations and Maintenance Requirements

The waste vitrification process operates 24 hours/day, 7 days/week. Startup and shutdown of the process can be accomplished in a few hours. Certain maintenance activities, described below, are performed periodically:

- changing decontamination solution in the decontamination solution tank and routing the used solution to a concentrator feed tank
- jetting the sump solutions to a waste collection tank for sampling
- regenerating the ruthenium sorber with dilute nitric acid or hot water, which is routed to a concentrator feed tank
- decontaminating equipment by flushing and routing the decontamination solution to a concentrator feed tank
- repairing occasional seal weld leaks or overpacking an off-standard canister.

Maintenance requirements for the waste vitrification facility are characteristic of fully-remote, high-radiation operations. Maintenance or replacement of equipment in this type of operation is from two to ten times more time consuming than for hands-on equipment. Equipment reliability is, therefore, a prime consideration.

B.1.1.4 Waste Vitrification Staffing Requirements

The waste vitrification facility staffing requirements are shown in Table B.2.

TABLE B.2. Waste Vitrification Staffing Requirements

Job Description	Personnel Required Man-yr/yr
Operators	19
Radiation Monitors	1
Maintenance Craftsmen	9

B.1.2 Waste Assay, Inspection, and Certification

The LLW and TRUW waste assay concept considered in this conceptual engineering study is quite similar to the concepts developed by the staff at BNFP. However, two independent lines are provided here--one for material that has to be handled remotely and one for material that can be handled via contact means. The WAIC facility is located on the west side of the WPF directly adjacent to the waste vitrification operation as shown in Figure B.1.

B.1.2.1 Waste Assay Facilities

The assay operation will share common mechanical systems, utilities, maintenance shops, security and administrative areas of the WPF with the vitrification operation. Remotely handled casks and drums will be received on the north side of the facility (Figure B.3), and the drums will be transferred into the receiving storage area remotely via overhead cranes and hoists. The drums that can be handled by contact methods will be received at the dock on the west side of the WPF and moved into the contact-handled receipt storage area. A basic process flow diagram is shown in Figure B.14. The contact-handled drums will be individually assayed by a passive gamma system. Higher level drums will pass through passive and active neutron interrogation systems to measure the total uranium/plutonium and the contents of fissile isotopes of both elements.

Overhead bridge cranes and installed material handling systems will assure adequate, semi-remote or remote handling of drums from receiving, through assay, and to shipping or interim storage as required. Provisions are also included for the remote transfer of drums as required between the remote and the contact handled lines.

Shielding walls are provided to maintain less than 0.1 mrem/hr dose rate in the operating galleries; less than 1 mrem/hr in the ventilation exhaust room and 10 mrem/yr in the neutron assay cell (with source retracted and calibration drums in closed wells). Additional shielding evaluations will have to be made to assure that reasonable background levels for gamma prescanning, passive gamma, and passive neutron measurements can be maintained with a minimum of operational sequence scheduling.

The assay process and building as depicted in Figures B.2 through B.6, has the capacity to process and monitor the wastes generated in a 1500 MTU/yr reprocessing plant. The quantity and classification of this waste is shown in Table B.3. The annual throughput of material is intended to be processed through the assay operation in 300 days. Up to a six-month storage capacity for both the receipt and exit of the contact-handled drums and about one-month's capacity for both the receipt and exit of the remote-handled containers is provided.

More than ample surge capacity is provided indoors in the contact-handled drum receiving/storage and the remote-handled drum receiving/storage so that the assay process can operate on a seven-day schedule while receiving shipments on a five-day schedule.

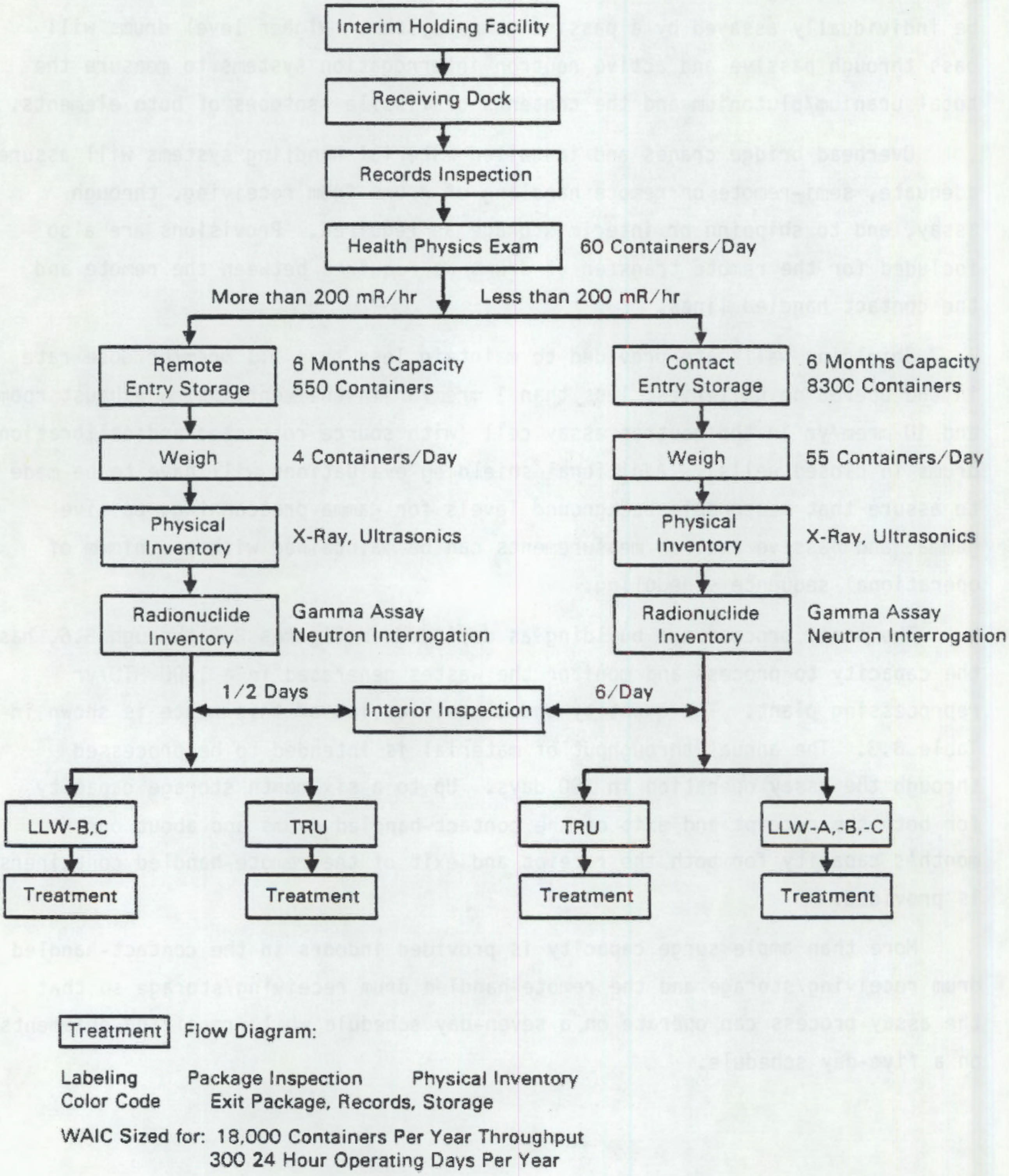


FIGURE B.14. WAIC Process Flow Diagram

TABLE B.3. Initial Containers Per Year in Low-Level and TRU Waste Classes

Container Size and Waste Type	Stream Number[(a)]	Drum/yr in Indicated Low-Level Waste Class			Drum/yr of TRU Waste in Indicated Dose Rate (mR/hr) Range				Totals			
		A	B	C	<200	$200-10^3$	10^3-10^4	$>10^4$	LLW	CH-TRU	RH-TRU	Total
55-Gal Drums Containing:												
General Process Trash (GPT)												
- From FRSS	13	625	--	--	--	--	--	--	625	--	--	625
- Segregated Combustible	27,28,29,47,48,53,65,66	6912	--	974	432	84	74.4	--	7,886	432	158.4	8,476
- Segregated Noncombustible	27,28,29,47,48,53,65,66	1728	--	243	108	21	18.6	--	1,971	108	39.6	2,119
- Total GPT									10,482	540	198	11,220
Failed Equipment	11A,51A	8	17	--	70	--	--	--	25	70	--	95
Particulate Solids	41,42,43	4035	--	327	--	93	--	--	4,362	--	93	4,455
Metal-Framed Filters	26B,52B	10	--	--	50	--	--	--	10	50	--	60
Total in 55-Gal Drums									14,879	660	291	15,830
80-Gal Drums Containing:												
Wood-Framed Filters	12,25A,25B,26C	15	20	25.5	153	52	12	--	60.5	153	64	277.5
Metal-Framed Filters	25B,26A,26C,45,46,52A,63B, 63C,64	71	9	28.5	961	56	13	--	108.5	961	69	1,138.5
Total in 80-Gal Drums									169	1,114	133	1,416
600-Gal Drums Containing:												
Hulls and Hardware	21	--	--	--	--	--	--	300	--	--	300	300
Failed Equipment	11B,24,44,51B,62	19	6	13	4	1	2	1	38	4	4	46
Metal-Framed Filters	25C,63A	--	--	--	--	--	--	44	--	--	44	44
Sample and Analytical Cell (SAC) Waste	23,67	--	--	4	--	28	6	3	4	--	37	41
Total in 600-Gal Drums									42	4	385	431
Total All Drums									15,090	1,778	809	17,677

(a) Data and stream numbers are taken from Darr (1983) for reprocessing 1500 MTU/yr.

Note: (1) Container weights not included in defining TRU level.
(2) Wastes from iodine retention operations not included (78 55-gal drum/yr).
(3) Values may be converted to container/MTU by dividing by 1500.

B.1.2.2 Waste Assay Equipment

The WAIC facility includes a variety of gamma ray spectroscopy, x-ray, and neutron-detection devices. Gamma devices are also used to assess container surface contamination levels. Containers with excessive surface contamination will be decontaminated.

Real time x-ray devices will be used to identify the contents of waste containers. x-ray devices identify the size, shape and density of the materials in a container. This information can be used to determine if the container holds combustible materials, free liquids, particulates and sludges (McKinley et al. 1983).

Neutron detection devices will be used to segregate TRU from non TRU bearing waste containers. They will be used along with gamma detection devices to inventory the isotopes present in containers shipped to federal repositories.

These detected neutrons are commonly categorized as passive (those emitted spontaneously by the waste) or as active (those emitted following interrogation of the waste with pulsed neutron or photon sources) emissions.

Active neutron interrogation techniques measure either the prompt or delayed fission neutrons or the beta delayed neutrons from fission products following induced fission. These techniques normally measure fissile transuranics (U-235, Pu-239, and Pu-241) and have been extensively applied to contact handled wastes (Kunz et al. 1981, Kunz and Caldwell 1982, Crane 1980). Active neutron interrogation has also been applied to high gamma activity wastes for the last several years (Kunz 1983, Caldwell and Kunz 1982, Close et al. 1983, Caldwell et al. 1983a, Barna et al. 1983, Caldwell et al. 1983b). The most prominent active neutron interrogation method is the differential die-away technique (DDT).

In the DDT, a pulse of fast (14-MeV) neutrons is introduced into an assay chamber made of polyethylene and lined with graphite where the pulse is thermalized. These neutrons have a characteristic lifetime called the system die-away time. If fissile material is present in the chamber, some of the neutrons will cause fissions. Prompt neutrons from these fissions are detected in specially designed neutron detectors, that "sense" these fast neutrons but are insensitive to the interrogating thermal neutrons.

Passive neutron interrogation techniques are capable of measuring all transuranics except U-235 with adequate sensitivity and will work on both contact handled and high gamma activity wastes. The general approach is to utilize neutron sensitive proportional counters, such as BF_3-10 or He-3, to record the total spontaneous neutron emission rate of the package and compare that to known standards for quantitative determination of the transuranic concentrations in the unknown package (Brodzinski and Wogman 1978, Wogman et al. 1978, Brodzinski et al. 1979a, Rogers et al. 1983, Brodzinski et al. 1984).

Since the passive techniques are sensitive to a wider spectrum of transuranic isotopes than the active techniques and since they are substantially less complex and less expensive than the active systems, the passive neutron TRU assay technology is recommended for waste assay instrumentation when interrogation time is not a significant factor. Passive interrogation times of 10,000 seconds have been required to accurately assay higher activity wastes such as chopped, leached fuels hulls (Brodzinski et al. 1979b).

The continuous operation of the waste facility will require that passive gamma, passive neutron, and active neutron techniques be used to reduce typical cycle times to less than 1 hr/drum. The specific array of monitoring instruments that will work most efficiently in the WAIC facility will have to be empirically determined.

The current design assumes that approximately 18 min/drum will be required for the gamma prescan, and 40 min/drum for the neutron assay. A 10 min/drum background count of neutrons followed by a 30 min/drum count of delayed neutrons released after active interrogation was assumed to be sufficient to provide the accuracy and precision needed to characterize the special nuclear materials (SNM) that are contained in each drum to acceptable levels of confidence.

The assay systems will be able to handle either 55-, 80- or 600-gal drums of waste. The time to process an 80-gal drum should not be significantly different from the time to process a 55-gal drum. However more development work will be required to establish the time required to handle, assay, and process 600-gallon containers.

B.1.3 Cost Estimate for WPF-1

A breakdown of the estimated capital and operating costs of the individual components of WPF-1 is given in Table B.4. Nearly 75 percent of the total capital cost is involved in the vitrification facility. The cost of the vitrification facility is based on that reported by Rogell and Steneck (1983) for a facility that is very similar to the one described in this report. More details of this estimate are contained in Tables B.5 and B.6.

B.2 DESCRIPTION OF WPF-2 (COMPACTION-ALTERNATIVE 2)

The waste treatment processes housed in WPF-2 are 1) waste vitrification, 2) waste assay, inspection and certification, and 3) waste compaction. A general plot plan and arrangement for WPF-2 are shown in Figure B.15. The total capital cost for WPF-2 is estimated to be about $259 million and the operating cost is estimated to be $24.8 million/year. Additional details are contained in the following discussion.

B.2.1 Waste Vitrification in WPF-2

The waste vitrification requirements, facilities, equipment, and costs are identical to those for WPF-1 (Section B.1.1).

B.2.2 Waste Assay, Inspection, and Certification in WPF-2

The waste assay, inspection, and certification requirements in WPF-2 are somewhat different from those in WPF-1. Major differences are described below.

1. The number of containers to be assayed is increased by the need to assay the containers of treated waste as well as the containers of waste before treatment.

2. The number of containers to be inspected and certified is decreased because of the reduced waste volume.

TABLE B.4. Capital and Operating Cost Estimates for WPF-1

Facility	Capacity	Capital Cost		Operating Cost, $ Million/yr			
		$ Millions	Reference	Fixed	Variable	Support	Reference
HLLW and ILLW Solidification	Hydraulic - 200 L/hr Glass - 1,320 kg/day	166	a	1.3	6.2	--	d
Hulls Storage (pre-assay)	12,000 ft^3	9	b	0.7	--	--	b,c
Hulls Storage (post-assay)	12,000 ft^3	10	b	0.7	--	--	b,c
WAIC	18,000 drums/yr	31	d	--	1.7	--	b,c
CH-TRU Storage (pre- and post-assay)	1,800 drums	1	b	0.6	--	--	b,c
RH-TRU Storage (pre- and post-assay)	900 drums	5	b	0.6	--	--	b,c
Other		5		0.3	--	9.5	
TOTALS		227		4.2	7.9	9.5	

(a) Costs are given in mid-1984 dollars.

(b) References are as follows: a = Rogell and Steneck 1983; b = AGNS 1978; c = Anderson and Evans 1983; d = memorandum from W. Knox, of AGNS, to L. R. Dodd, PNL, 1983.

(c) WAIC costs consist of $20 million (from Knox, AGNS) plus $10 million to accommodate hulls assay facilities (PNL estimate).

(d) Based on 1.95 man-yr of support labor for each man-yr of direct operating labor.

TABLE B.5. Principal Assumptions for the Solidification Facility Cost Estimate

Item	Design Value
Process Variables	
Melter Design Capacity	1320 kg/d 200 ℓ/hr
Canister Storage Pool	133 ft x 108 ft x 30 ft
Operating Variables	
On stream time	300 d/yr
Operating cycle	24 hr/operating day
Replication	2 melters each at 100% design One in use, one spare

TABLE B.6. Direct, Indirect and Contingency Costs for the Solidification Facility Cost Estimate

Item	Cost Estimate ($ Millions)	
Direct Costs		
Major equipment, tanks, vessels, melters, etc.	17.0	
Bulk materials (including concrete, structurals, pipe, liner plates, etc.)	15.8	
Direct labor	34.5	
Subcontracts	3.8	
Subtotal Direct Costs	71.3	71.3
Indirect Costs		
Indirect Costs/Distributables	35.5	
Engineering Costs/Fee	26.2	
Subtotal Indirect/Engineering Costs	61.7	61.7
Contingency		
Total Capital Cost (±25%)		33.0
		166.0

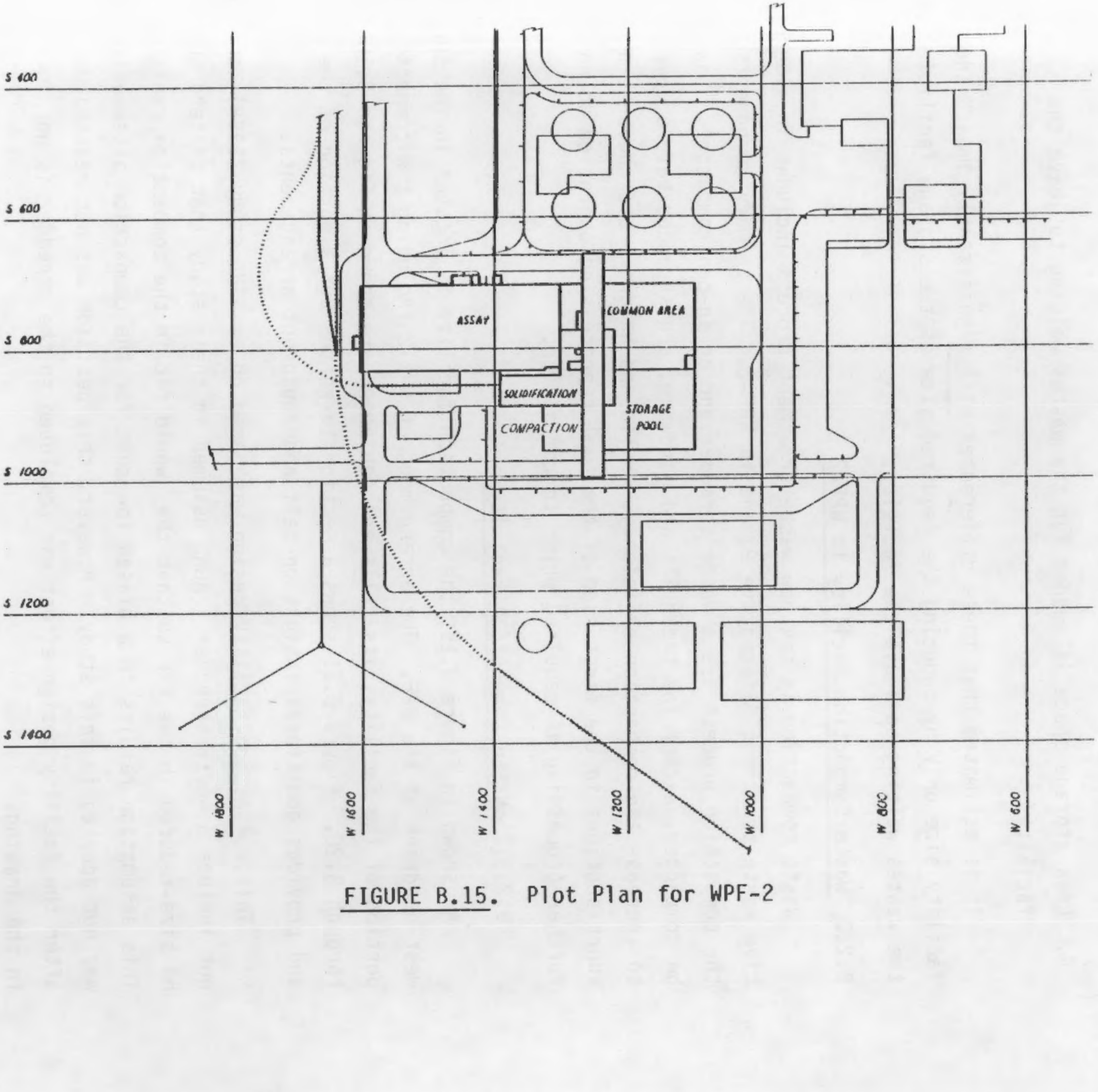


FIGURE B.15. Plot Plan for WPF-2

3. An additional container type, the 160-gallon compaction canister, must be assayed, inspected, and certified.
4. Less storage space is needed for the wastes waiting to leave the facility.

It is estimated that these differences will significantly impact the facility size only by reducing the required size of the storage facilities for the wastes waiting to leave the facility.

B.2.3 Waste Compaction Facility in WPF-2

Waste compaction is the new waste treatment process included in alternative waste treatment Alternative 2, and in WPF-2. The primary components of the compaction process are a waste shredder and an in-can compactor. Wastes to be compacted, except for the hulls and hardware, are shredded before compaction to increase the compaction efficiency. Hulls and hardware are chopped into short sections in the first step of the fuel reprocessing operation so no further processing is required prior to compaction.

B.2.3.1 Waste Compaction Facility

As shown in Figure B.15, the compaction facility is located in the southwest quadrant of the WPF. The arrangement of WPF-2 including the compaction portion of the facility, its cells and equipment are shown in Figures B.16 through B.20. Figure B.21 shows a section taken through a portion of the WPF and provides additional insight on cell and equipment arrangements.

This compaction facility design was based on an AGNS study (1978), and did not include a waste shredder. AGNS assumed in their study that filters would be size-reduced in the FRP so that they would fit in the compaction canister. This assumption results in a biased low cost for the compaction alternative and was not adopted in this study. However, this decision was not reached until after the facility design effort was completed so the shredder is not included in the drawing.

The design of this portion of the WPF follows the general concepts used in the other parts including: 1) provision for receiving and shipping process materials, 2) allowance for transferring process material to other processes as

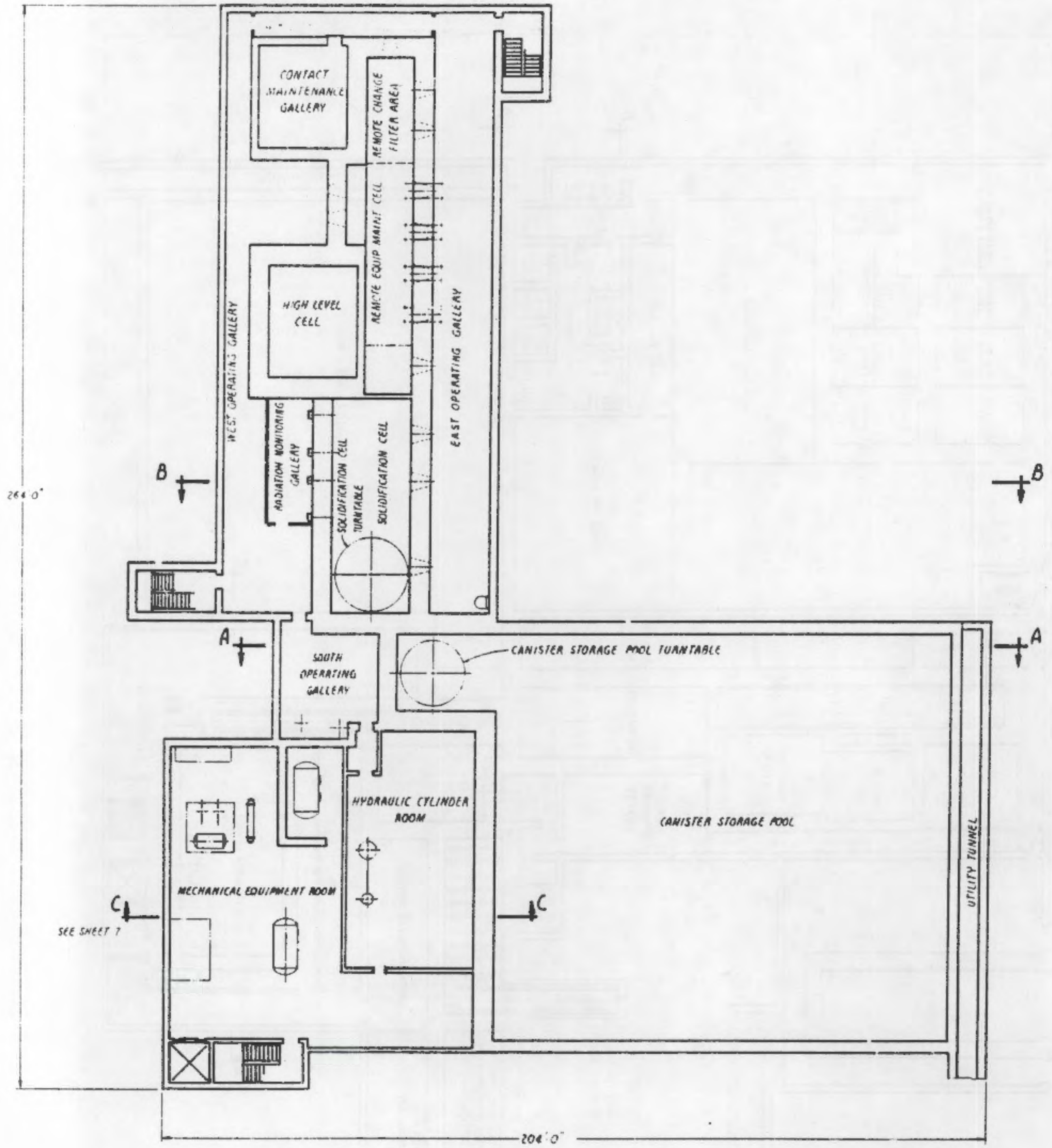


FIGURE B.16. Floor Plan for WPF-2 at Elevation 236'-0"

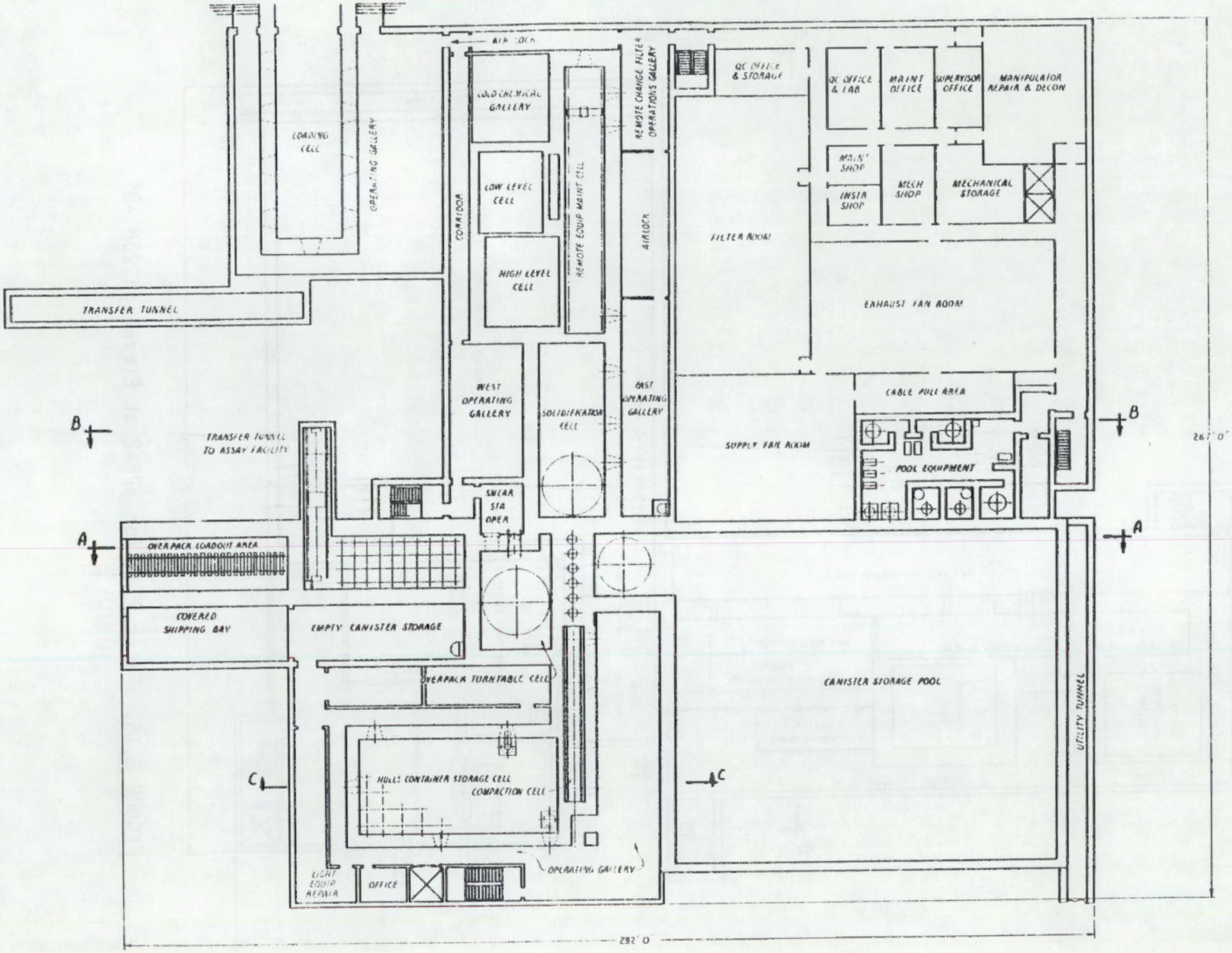


FIGURE B.17. Floor Plan for WPF-2 at Elevation 250'-0"

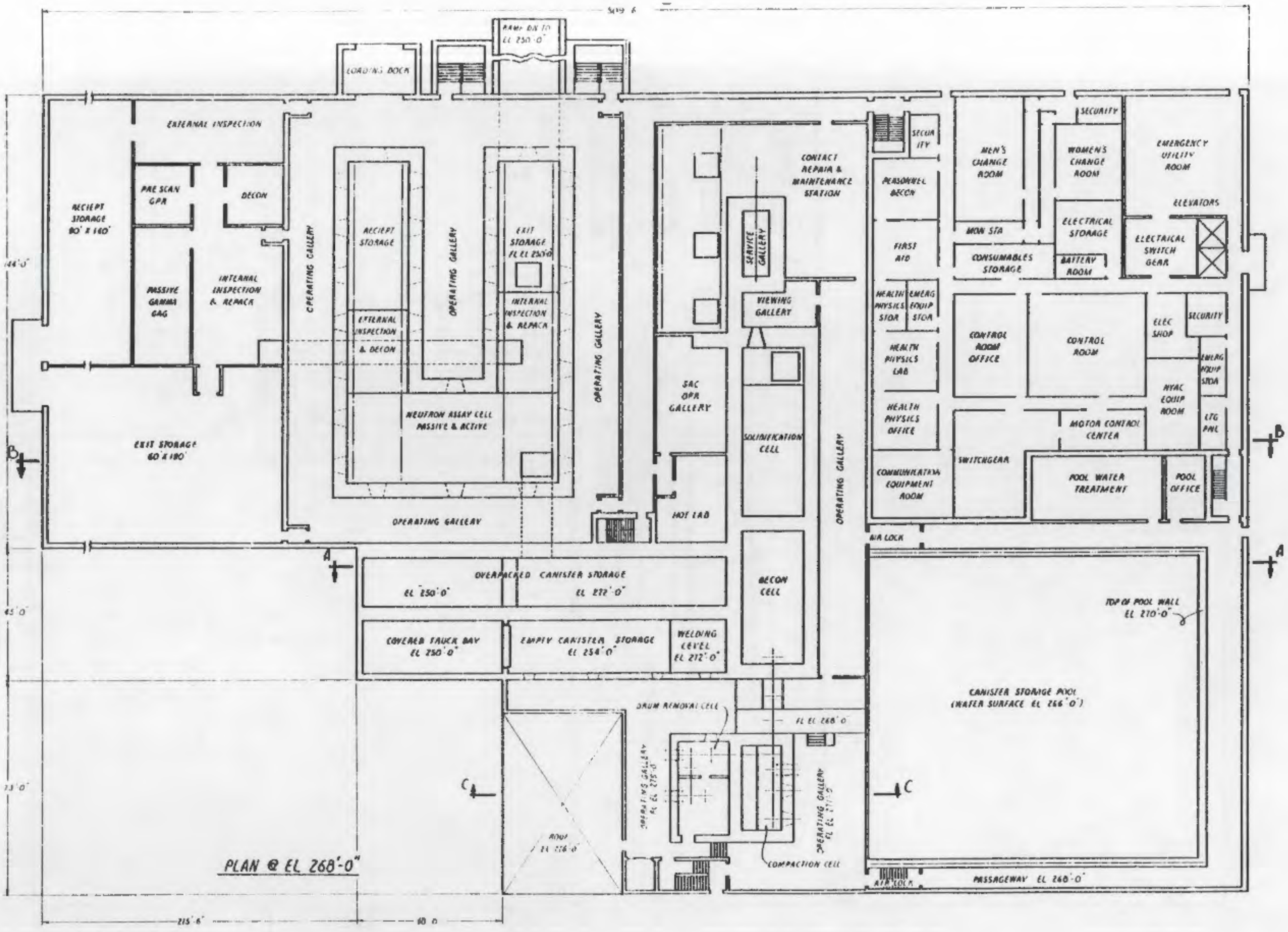


FIGURE B.18. Floor Plan for WPF-2 at Elevation 268'-0"

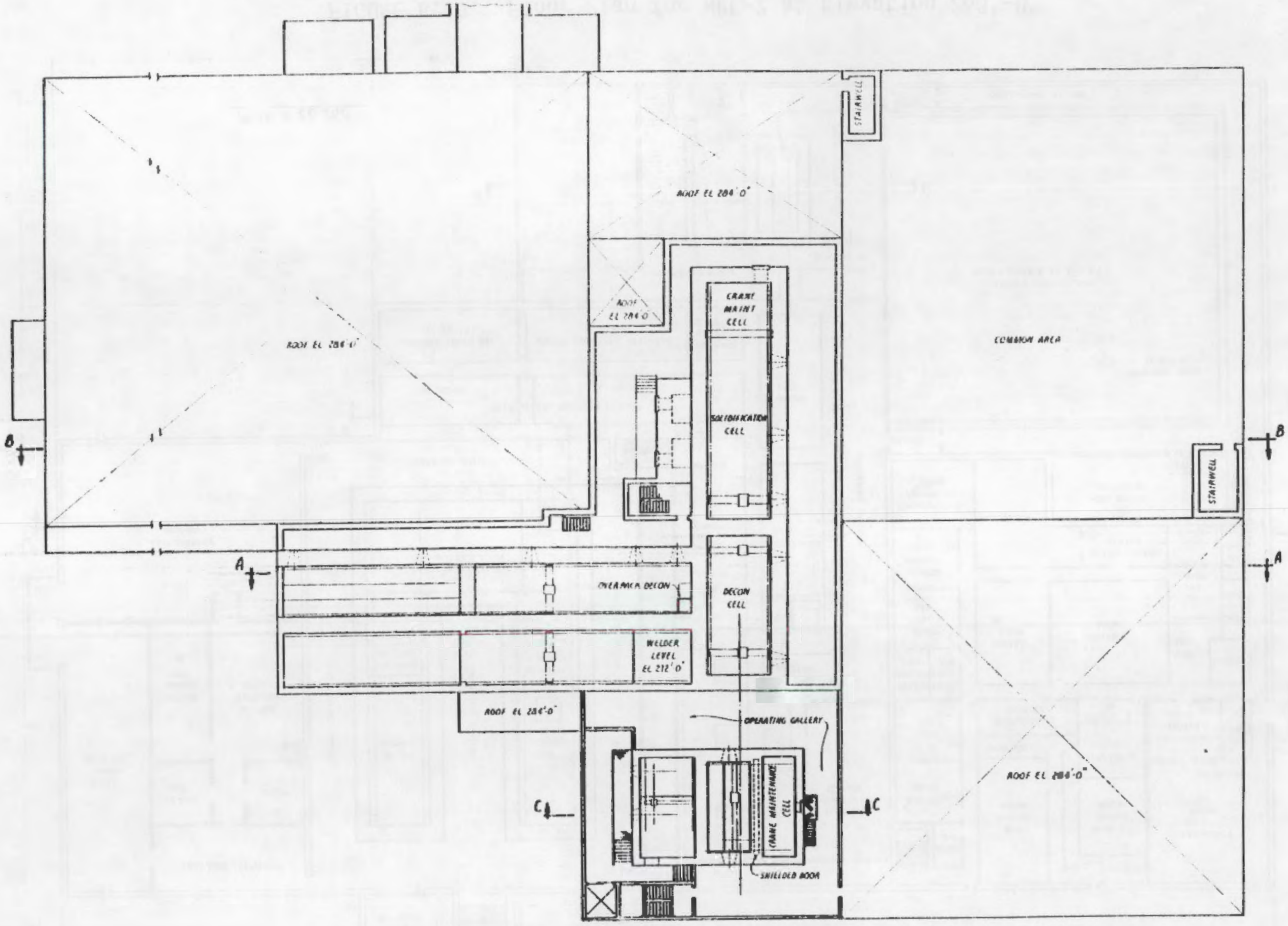


FIGURE B.19. Floor Plan for WPF-2 at Elevation 284'-0"

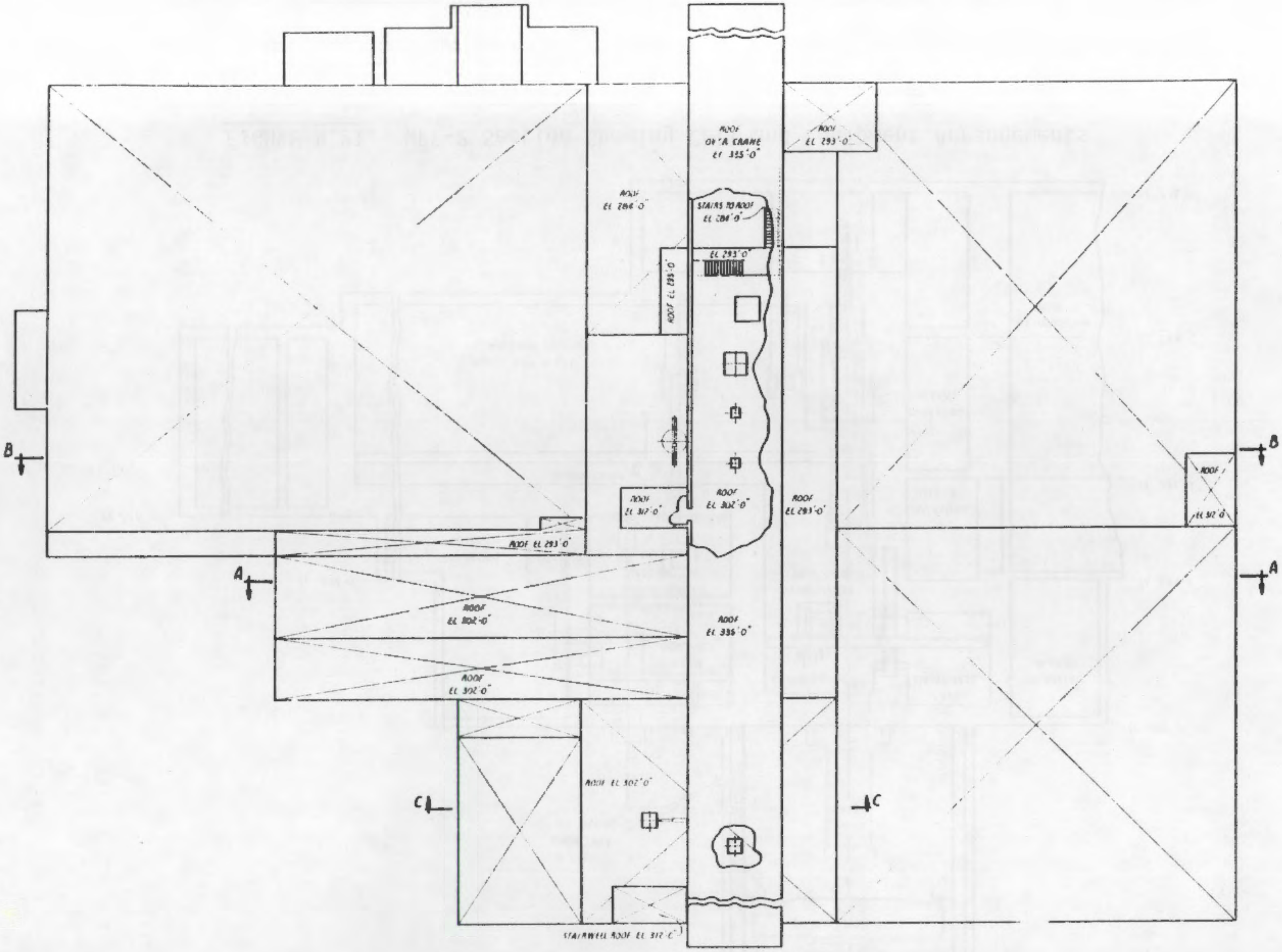


FIGURE B.20. Floor Plan for WPF-2 at Elevation 335'-0"

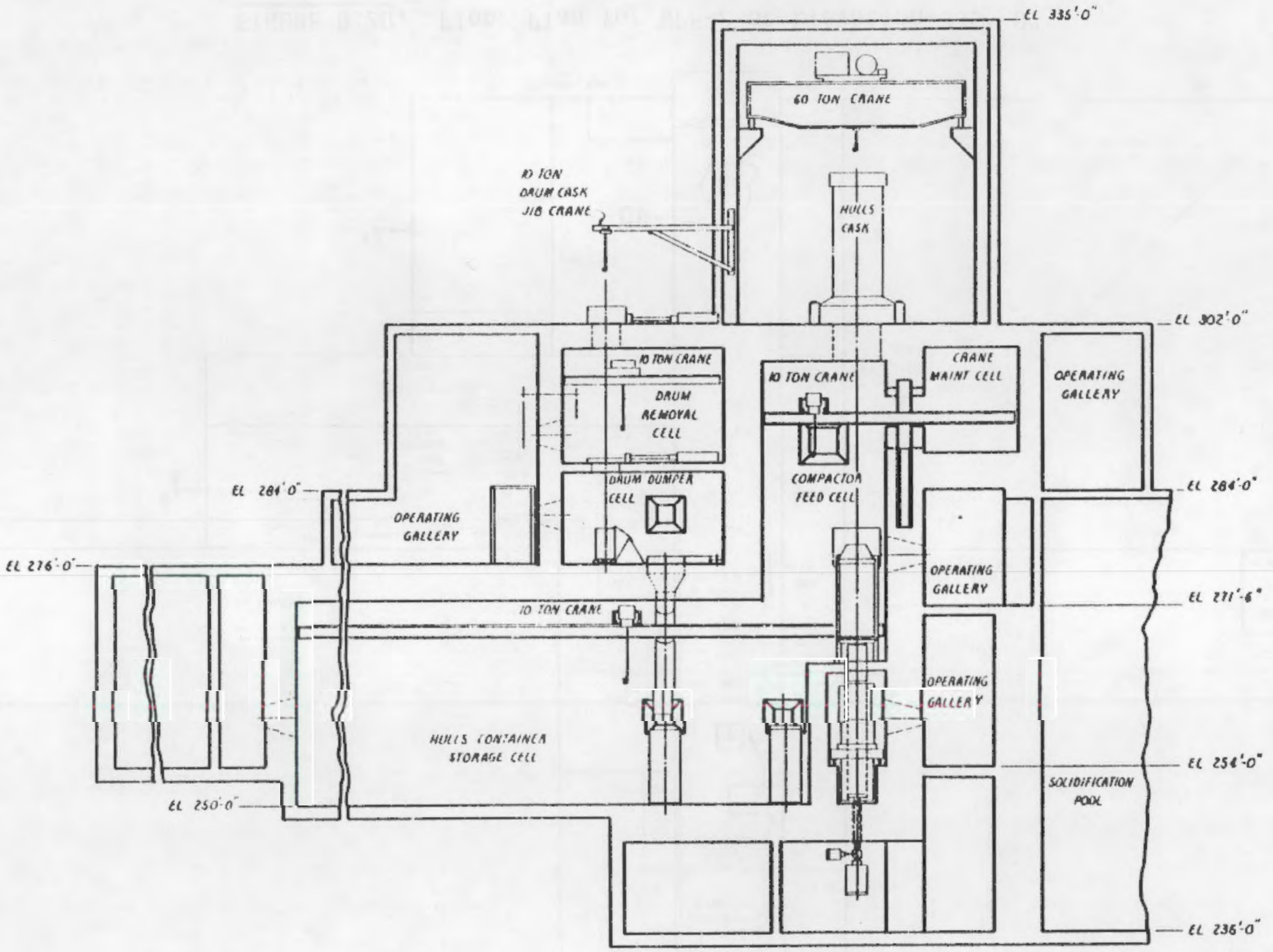


FIGURE B.21. WPIF-2 Section Showing Cell and Equipment Arrangements required, 3) hot cells with supporting services and galleries for operation and maintenance, and 4) areas for associated activities that are not required to be performed remotely.

The facility will be constructed of normal density concrete. Most cell walls will be between 3 to 4 ft thick. The first floor of the facility will be underground and all external walls will be at least 18 in. thick to support soil loadings.

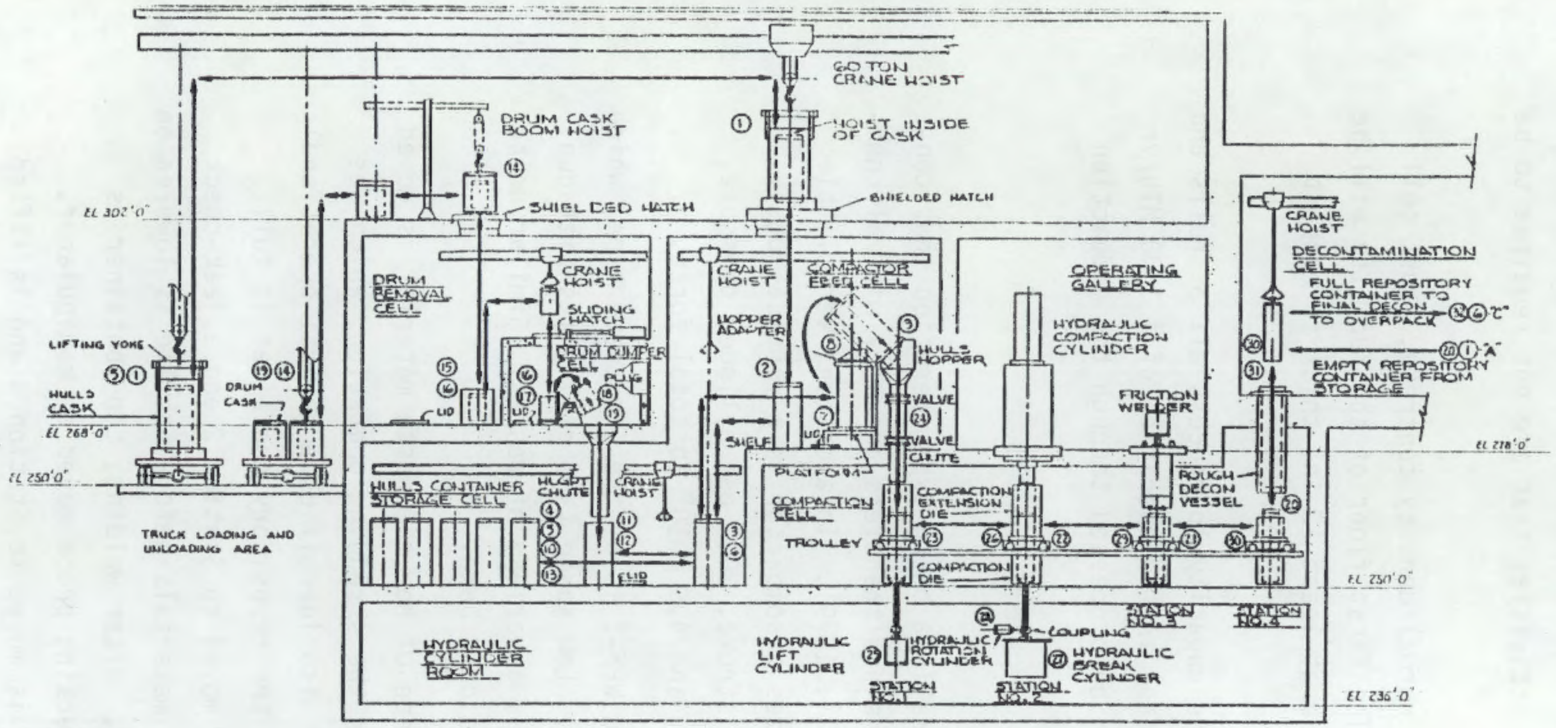
This process is sized for and has the capacity to process all of hulls and the other compactable TRUW and LLW generated in the operation of a 1500 MTU/yr reprocessing facility. This material can be processed through the compaction process in 300 days.

B.2.3.2 Waste Compaction Equipment

The cold compaction process is basically a batch-type operation that consists of a number of mechanical operations and transfers and very minimal chemical processing or changes (Anderson et al. 1979). In addition, very little off gas is generated. The process utilizes a compactor in a vertical position. It is designed for an 8 ft 11 in. stroke, 3000 psi cylinder pressure, 10,000 psi developed compaction pressure, and 4.5×10^6 lb total force.

The shredder chosen for inclusion in WPF-2 is of the low speed type, which has recently undergone extensive testing. Low speed (<60 rpm) units with dual counter-rotating shafts were used to shred a variety of wastes. Similar units should work well in the application envisioned here.

Figure B.22 shows the general sequence of how the waste material is moved into and through the facility (except for the shredding operation, which was incorporated into the design later). It also identifies a general operational sequence of process material flow. When the repository container is full (Step 26, Figure B.22), the container is moved to Station 2 and a leak-check source is placed on top of the compacted materials before the lid is lowered on the container prior to welding (Step 29). After welding, the container is leak-checked at Station 3 with a leak-checking probe moved by manipulator. When the seal is confirmed the container is moved to Station 4 and is lifted through the floor plug into the decontamination cell by crane.



1. Move hulls cask from truck to shielded hatch on upper level via 60 ton crane hoist.
2. Lower hulls container from inside hulls cask to shelf in compactor feed cell via hoist inside of hulls cask.
3. Move hulls container from shelf to storage cell via compactor feed cell crane hoist.
4. Move hulls container to storage position via hulls container storage cell crane hoist.
5. Reverse sequence of Nos. 1 thru 4 to move empty hulls container from storage to hulls cask and hulls cask to truck.
6. Move full hulls container from storage via hulls container storage cell crane hoist, to start compaction process.
7. Using compactor feed cell crane hoist, move hulls container to container dumper platform.
8. Using mechanical manipulators, remove lid, position and fasten hopper adapter.
9. Using compactor feed cell crane hoist, transfer hulls container contents to hulls hopper.
10. Reverse sequence of Nos. 4, 7, 8, 9 to return empty hulls container to storage.
11. Using hulls container storage cell crane hoist, position empty hulls container under HLGPT chute.
12. Using mechanical manipulators, remove hulls container up.
13. Reverse sequence of Nos. 11 and 12 to move full hulls (HLGPT) container to storage.
14. Move HLGPT drum cask from truck to position on upper level adjacent to drum cask boom hoist via 60 ton crane hoist.
15. Move drum cask thru shielded hatch to drum removal cell via drum cask boom hoist.
16. Using drum removal cell crane hoist, remove drum cask lid, move drum thru sliding hatch and position in drum dumper.
17. Using mechanical manipulators, remove drum lid and fasten drum in drum dumper.
18. Open chute plug and activate dumper.
19. Reverse sequence of Nos. 14 thru 18 to return empty HLGPT drum to cask and cask to truck.
20. Using decontamination cell crane hoist, obtain empty repository container (with lid tac-welded in place) from storage, insert empty container into compaction die thru rough decon vessel at station no. 4.
21. Move trolley to station no. 3, drop friction welder to lid, chuck lid, cut tac-welds, prep container and lid ends for welding, raise friction welder (lid retained), deposit weld flashing scrap from previous weld into empty container.
22. Move trolley to station no. 2, lift container with break cylinder, container lifts extension die, rotate coupling to release extension die, retract break cylinder to position extension die.
23. Move trolley to station no. 1, lift container with lift cylinder (container lifts extension die to encompass chute end)
24. Using chute valves, release HLGPT/hulls from hopper to fill container and extension die.control level with chute valve.
25. When desired level of loose/compacted material is obtained, retract lift cylinder.
26. Move trolley to station no. 2 for compaction, to station no. 1 for HLGPT/hulls loading, to station no. 2 for compaction, etc. until desired level of compacted material inside of container is achieved.
27. Using hydraulic break cylinder (at station no. 2), break container free by lifting container, container lifts extension.
28. Using hydraulics rotation cylinder, rotate coupling to position extension die for storage, retract break cylinder.
29. Move trolley to station no. 3. Drop friction welder, weld lid to container, raise friction welder, remove excessive flashing from container/lid weld. Retain scrap at station no. 3 until lid of next empty container is positioned in welder and welder raised.
30. Move trolley to station no. 4. Using decontamination cell crane hoist, left full repository container into rough decon vessel, close vessel bottom hatch, release container inside vessel, remove crane hoist.
31. Close top hatch of rough decon vessel, activate vessel for desired period of time, drain vessel, open top hatch.
32. Using decon cell crane hoist, lift full repository container into a repository overpack.

FIGURE B.22. Operational Sequence for Waste Compaction Facility

The container is sprayed with decontamination solution under high pressure from nozzles inside a spray booth. After decontamination, the repository containers are lifted by crane and placed in storage or they can be transferred to the WAIC facility via the tunnel (Figure B.17). From storage, a container can be taken to the loading bay and lowered by crane onto a transport vehicle.

Air flows from the compactor, the dumping device, and the remote welder pass through a venturi scrubber where the majority of the particulates are removed. The off gas is then cooled in the cooler-condenser, separated from the condensate in the separator, heated above its dew point in the reheater, and filtered through a roughing filter and a HEPA filter. The filtered off gas passes through redundant fans and is released to the building exhaust system.

B.2.4 Cost Estimate for WPF-2

A cost estimate for a compaction facility similar to that employed here was prepared during 1983 (Anderson and Evans 1983). The capital cost summary for that facility is included in Table B.7. The estimated cost was about

TABLE B.7. Compaction Facility Cost Estimate: Direct, Indirect and Contingency Costs

Item	Cost ($ Million)[a]
Major Equipment	8.6
Bulk Materials	2.4
Subcontracts	1.0
Direct Labor and Burden	5.6
Subtotal Direct	17.6
Indirect Costs/Distributables	6.1
Engineering/Fee	4.8
Subtotal	28.5
Contingency (30%)	8.5
TOTAL	37.0[b]

(a) Mid-1984 dollars Southeastern U.S. labor rates (Anderson and Evans 1983).

(b) Inclusion of a shredder and its ancillary equipment is estimated to increase this to $41 million.

$37 million. The current compaction facility design includes a shredder. This device was not included in the cost estimate developed by Anderson and Evans (1983). A shredder and its ancillary equipment and facilities are estimated to cost an additional $4 million giving a total cost of roughly $41 million for the compaction facility to be included in WPF-2.

Estimates of both capital and operating costs for all of the facilities included in WPF-2 are given in Table B.8. The $41 million capital cost of the compaction facility is partially offset by a reduction in storage facility costs resulting from the smaller volume of treated waste. The estimated capital cost for WPF-2 is thus $259 million, compared with $227 million for WPF-1 (a 14 percent increase). The operating cost is estimated to be $24.8 million/yr, compared with $21.6 million/yr for WPF-1 (a 15 percent increase).

B.3 DESCRIPTION OF WPF-3 (INCINERATOR/CEMENTATION PLUS COMPACTION-ALTERNATIVE 3)

WPF-3 includes facilities to incinerate the combustible TRUW and LLW and to immobilize the incineration residues in cement in addition to facilities for waste vitrification, for WAIC, and for waste compaction. The latter three facilities are similar or identical to those in WPF-2 except for differences in size, as discussed below. A general plot plan and arrangement for WPF-3 are shown in Figure B.23. The total capital cost for WPF-3 is estimated to be about $276 million and the operating cost is estimated to be $29.7 million/year.

B.3.1 Waste Vitrification in WPF-3

The waste vitrification requirements, facilities, equipment, and costs for WPF-3 are identical to those for WPF-1 (Section B.1.1) and WPF-2 (Section B.2.1).

B.3.2 Waste Assay, Inspection, and Certification in WPF-3

The WAIC facility in WPF-3 will be very similar to that in WPF-2 (Section B.2.2).

TABLE B.8. Capital and Operating Cost Estimates for WPF-2

		Capital Cost		Operating Cost, $ millions/yr			
Facility	Capacity	$ millions	Reference	Fixed	Variable	Support	Reference
HLLW and ILLW solidification	Hydraulic - 200 L/hr Glass - 1320 kg/day	166	a	1.3	6.2	---	d
Hulls Storage (pre-assay)	12,000 cu.ft.	9	b	0.7	---	---	b,c
Hulls Storage (post-assay)	3,800 cu.ft.	5	b	0.7	---	---	b,c
WAIC	18,000 drums/yr	31	d	---	1.7	---	b,c
CH-TRU storage pre & post assay	960 containers	1	b	0.6	---	---	b,c
RH-TRU storage pre & post assay	550 containers	1	b	0.6	---	---	b,c
Compaction	18,000 drums/yr	41	c	0.7	1.3		c
Other		5		0.3	---	10.7	
Total		259		4.9	9.2	10.7	

(a) Costs are given in mid-1984 dollars.

(b) References are as follows: a = Rogell and Steneck 1983; b = AGNS 1978; c = Anderson and Evans 1983; d = Memorandum from W. Knox, of AGNS, to L. R. Dodd, PNL, 1983.

(c) WAIC costs consist of $20 million from Knox (1983) plus $10 million to accommodate hulls assay facilities (PNL) estimate.

(d) Based on 1.95 man-yrs of support labor for each man-yr of direct operating labor.

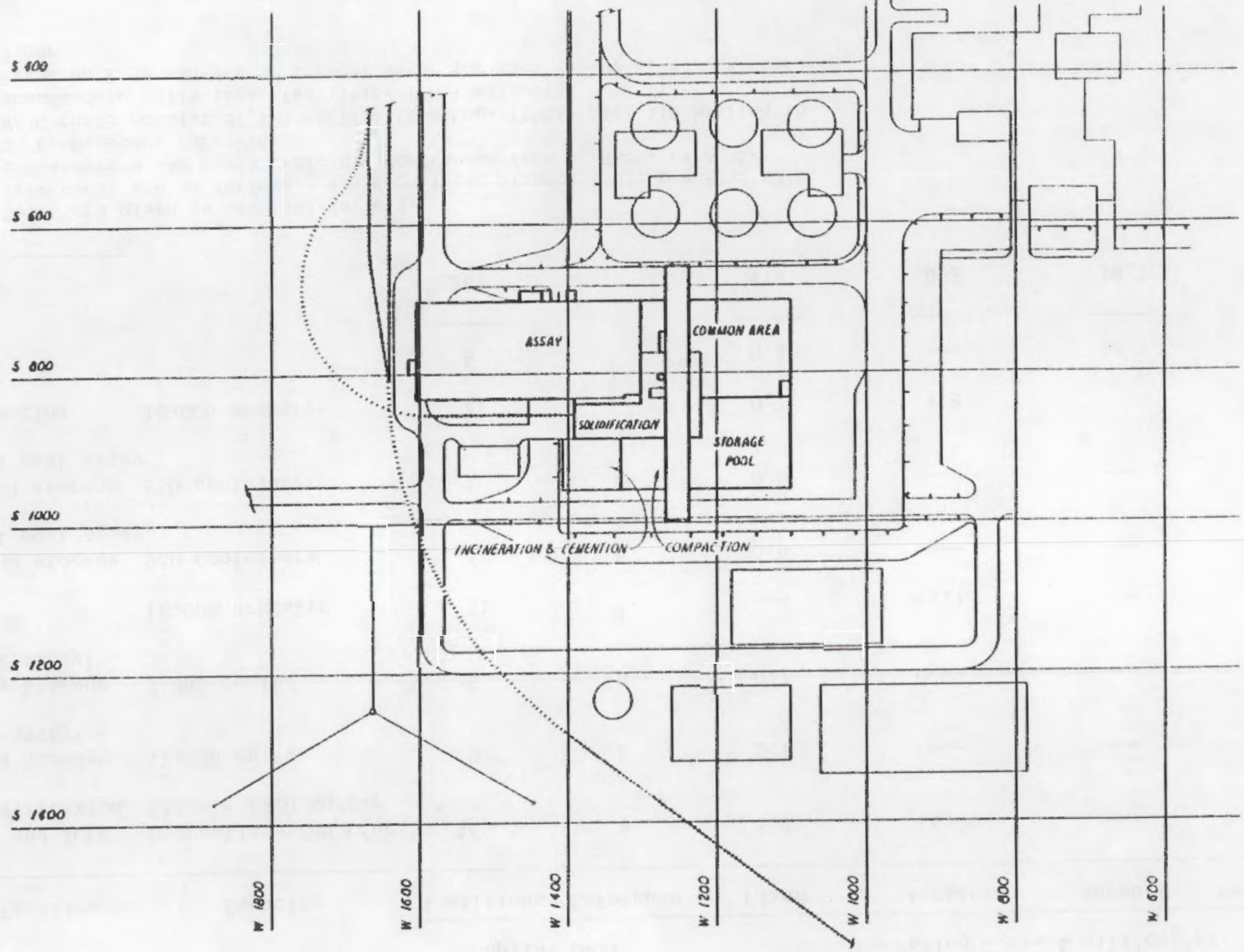


FIGURE B.23. Plot Plan for WPF-3

B.3.3 Waste Compaction in WPF-3

The compaction facility in WPF-3 will be very similar to that in WPF-2 (Section B.2.3), but will be of smaller size due to a lower waste throughput (some wastes that were previously compacted are incinerated). The shredder used to prepare the wastes for compaction in WPF-2 will not be included in the compaction facility of WPF-3 because the preponderant waste to be compact in this alternative case (hulls and hardware) has already been sheared in the FRP. However, a comparable shredder is included in the incineration facility.

B.3.4 Waste Incineration/Cementation in WPF-3

WPF-3 includes an incinerator to burn the combustible portions of the waste, thus decreasing the waste volume and destroying organic materials. It also includes a cementation process to immobilize both the particulate solids produced as primary wastes (e.g., fluorinator fines) and the secondary wastes (e.g., incinerator ash and off-gas scrubber solution).

B.3.4.1 Waste Incineration/Cementation Facility

As shown in Figure B.23, the incineration/cementation processes are located in the southwest quadrant of the WPF adjacent to the compaction process. The arrangement of WPF-3 including the incineration portion of the facility, its cells, and equipment are shown in Figures B.24 through B.28. Figure B.29 shows a section cut through this portion of WPF-3 and provides additional information on cell arrangement. The design of this portion of the WPF follows the general concept used in the other parts including: 1) provision for receiving and shipping process materials, 2) allowance for transferring process material to other processes as required, 3) hot cells with supporting services and galleries for operation and maintenance, and 4) areas for associated activities that are not required to be performed remotely. The facility will be constructed of normal density concrete. Most cell walls will be between 3- to 4-ft thick. The first floor of the facility will be underground and all external walls will be at least 18-in. thick to support soil loadings.

This process has the capacity to process all of the combustible trash generated in the operation of a 1500 MTU/yr reprocessing facility. This

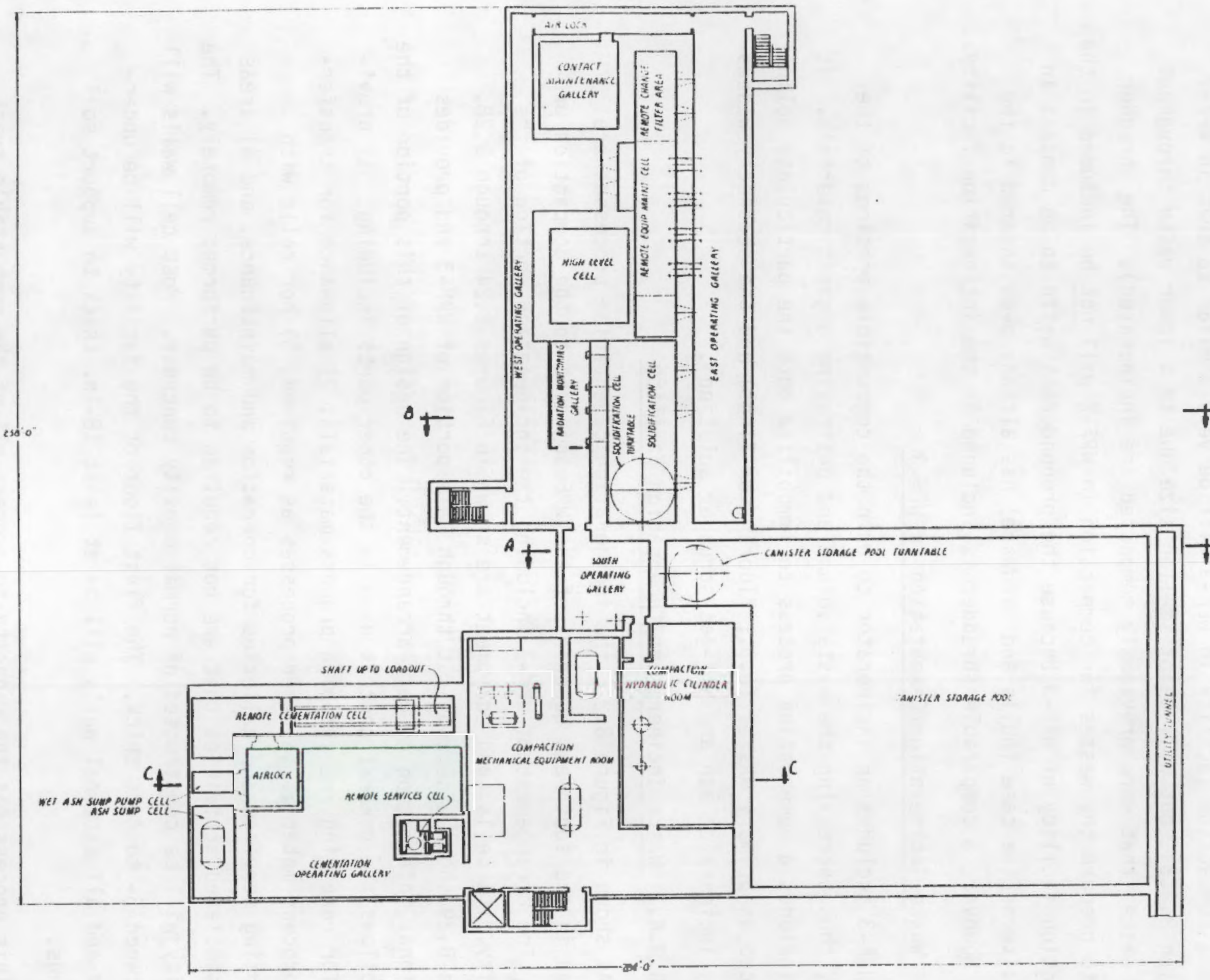


FIGURE B.24. Floor Plan for WPIF-3 at Elevation 236'-0"

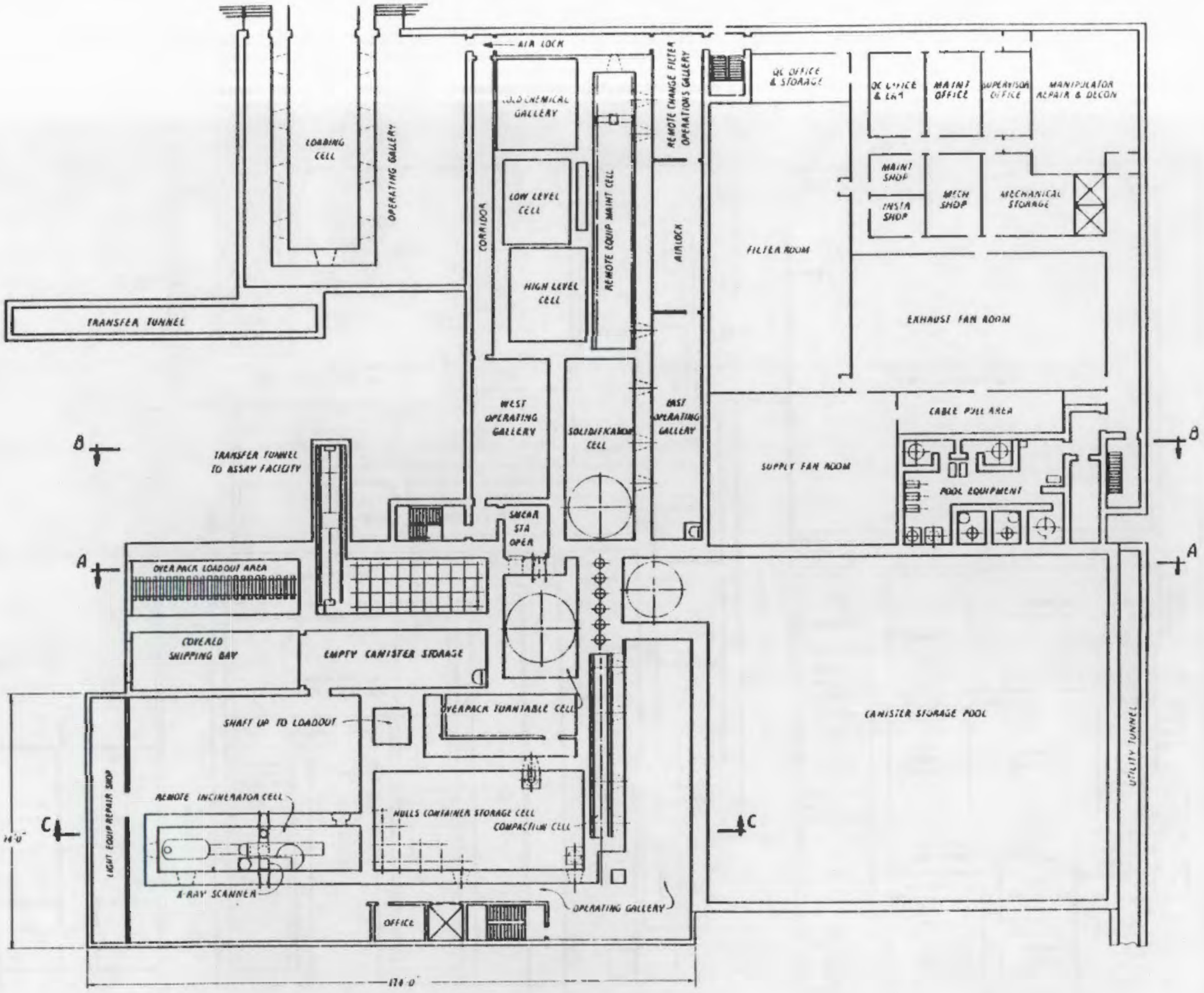


FIGURE B.25. Floor Plan for WPF-3 at Elevation 350'-0"

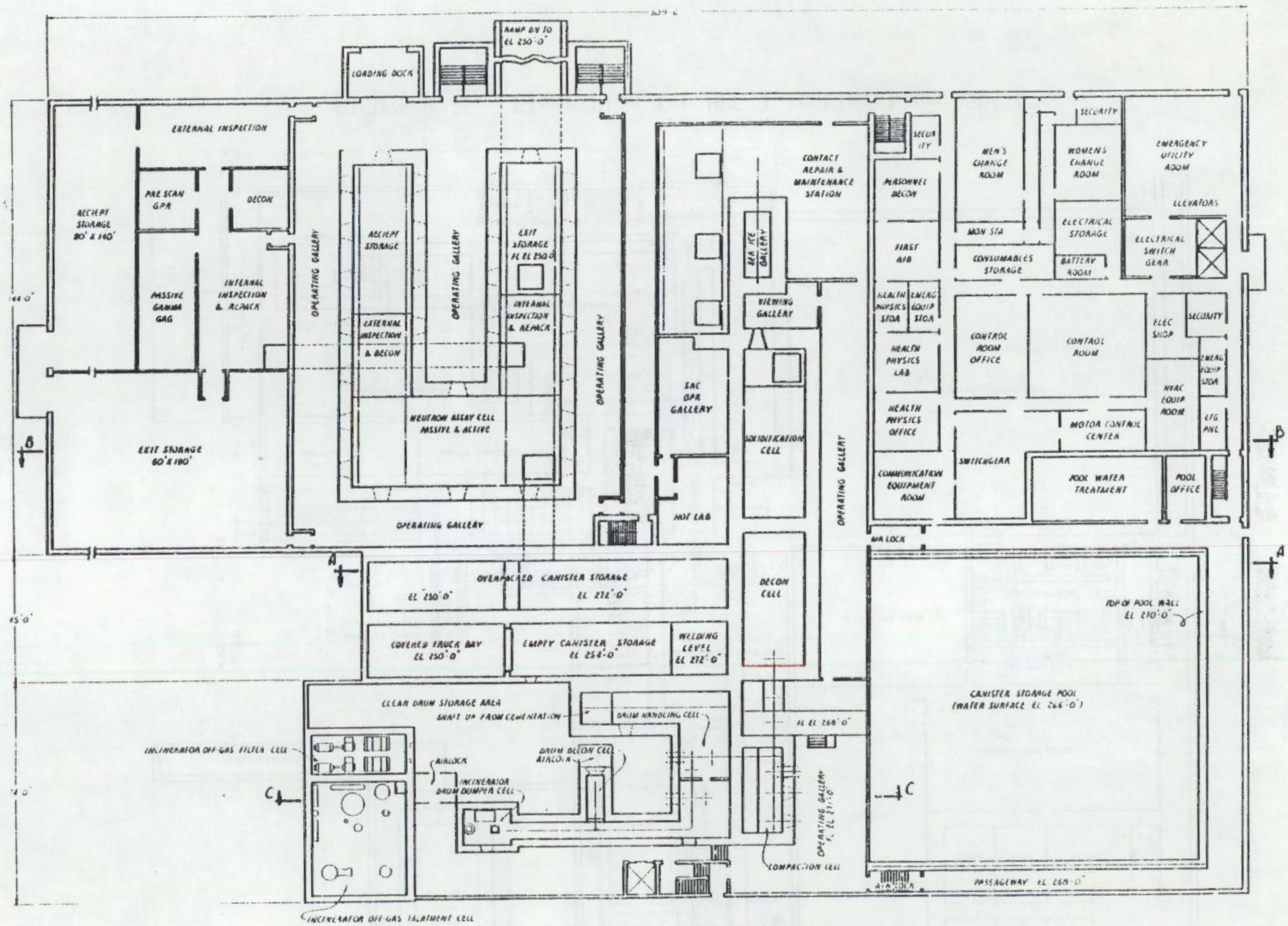


FIGURE B.26. Floor Plan for WPF-3 at Elevation 268'-0"

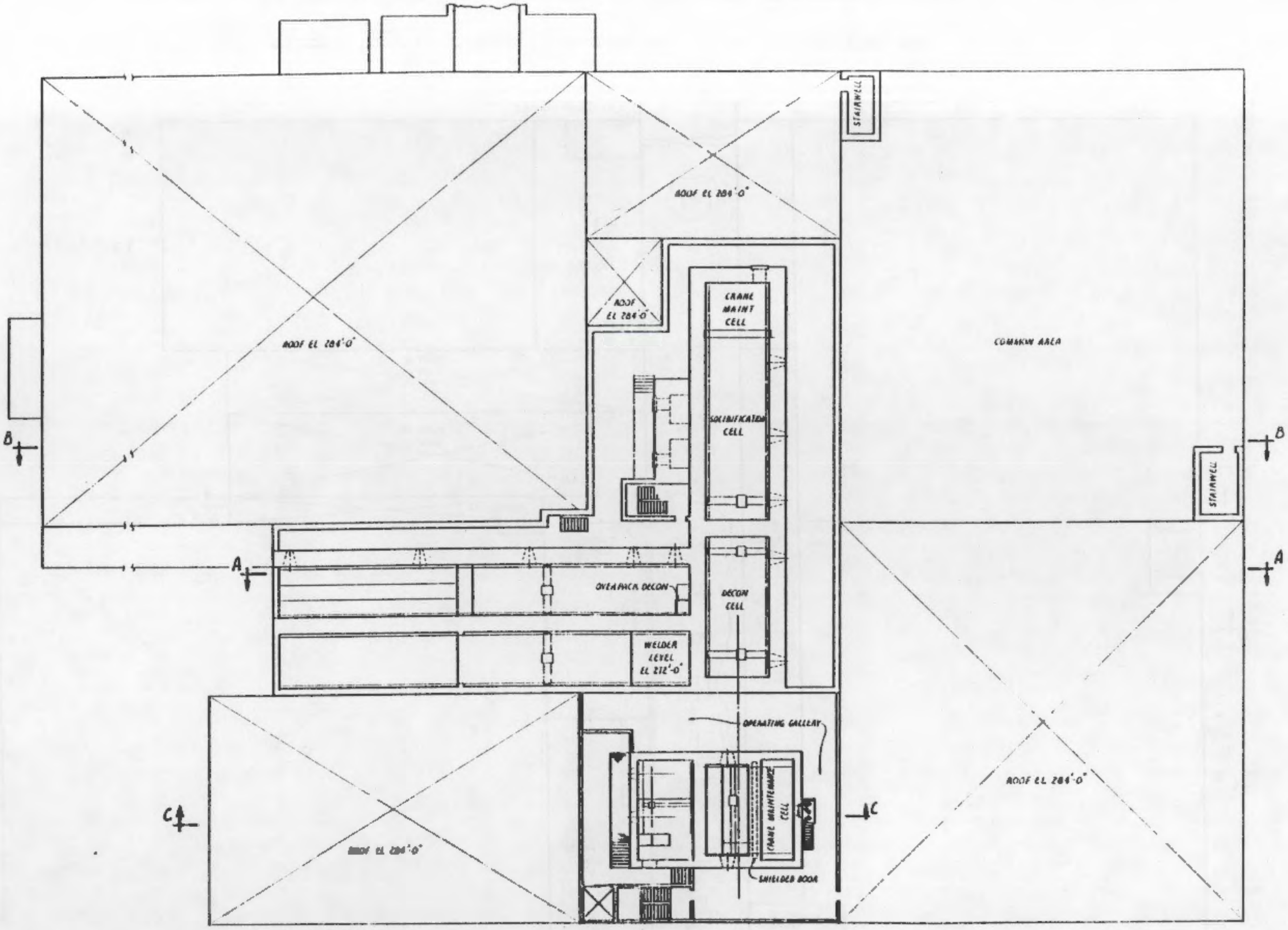


FIGURE B.27. Floor Plan for WPF-3 at Elevation 384'-0"

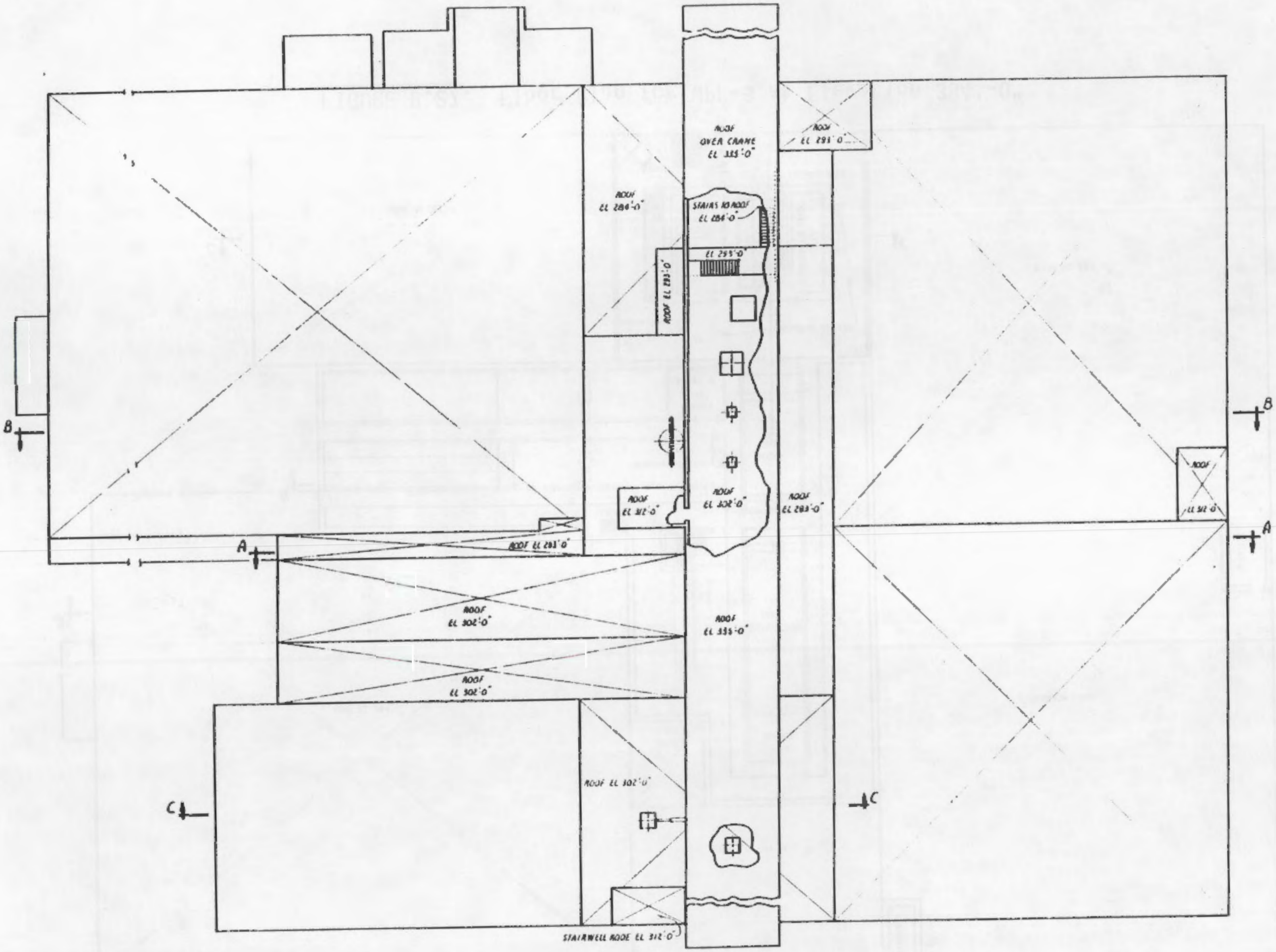


FIGURE B.28. Floor Plan for WPF-3 at Elevation 335'-0"

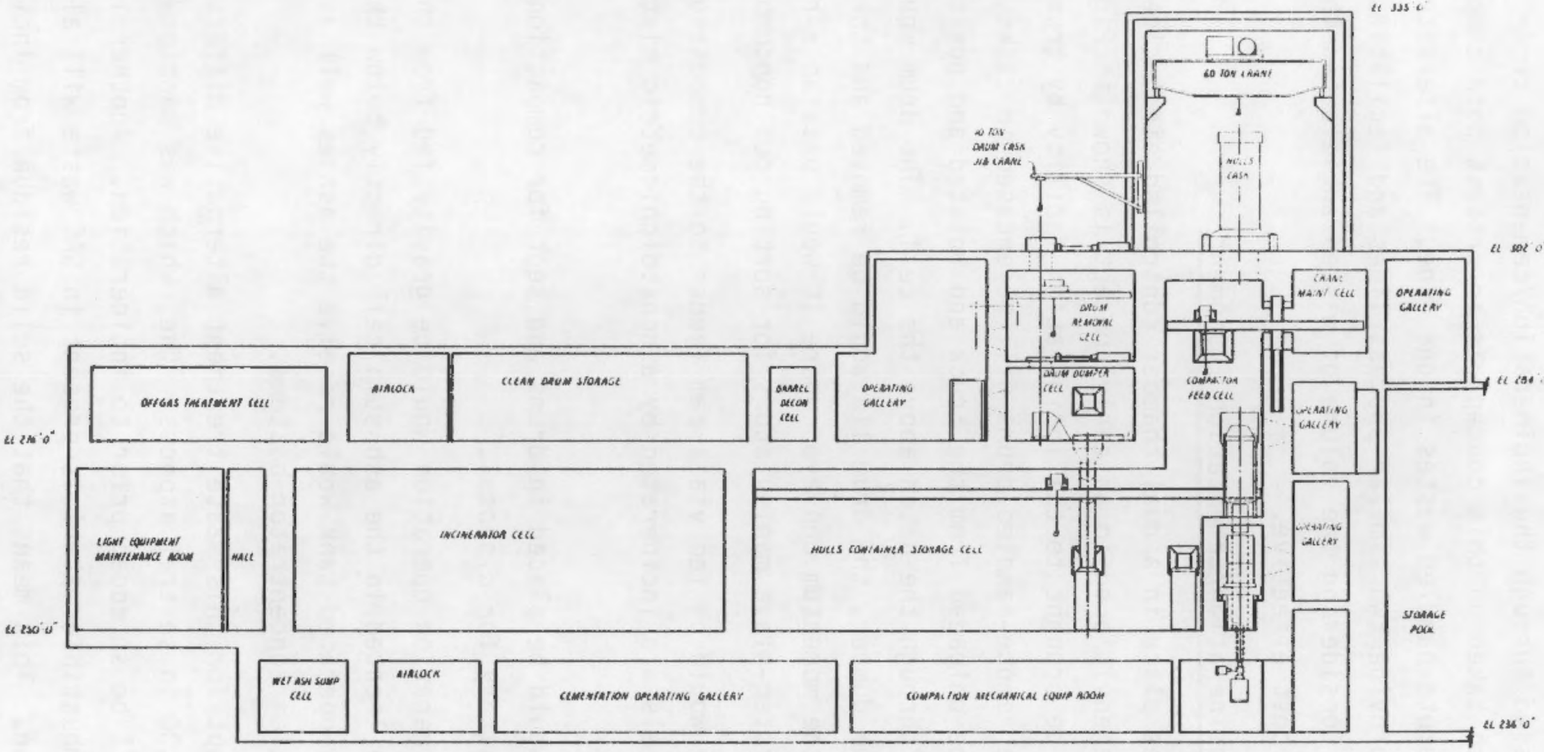


FIGURE B.29. WPF-3 Section Showing Cell and Equipment Arrangement Details material can be processed through the incineration/cementation processes in 300 days. The approach taken on this concept is to process both combustible contact-handled and remote-handled wastes in one line. The alternate to this approach would be to provide two similar process lines and facilities to support and house them. Considering the volume of wastes anticipated this latter approach would not be cost effective.

B.3.4.2 Waste Incineration/Cementation Equipment

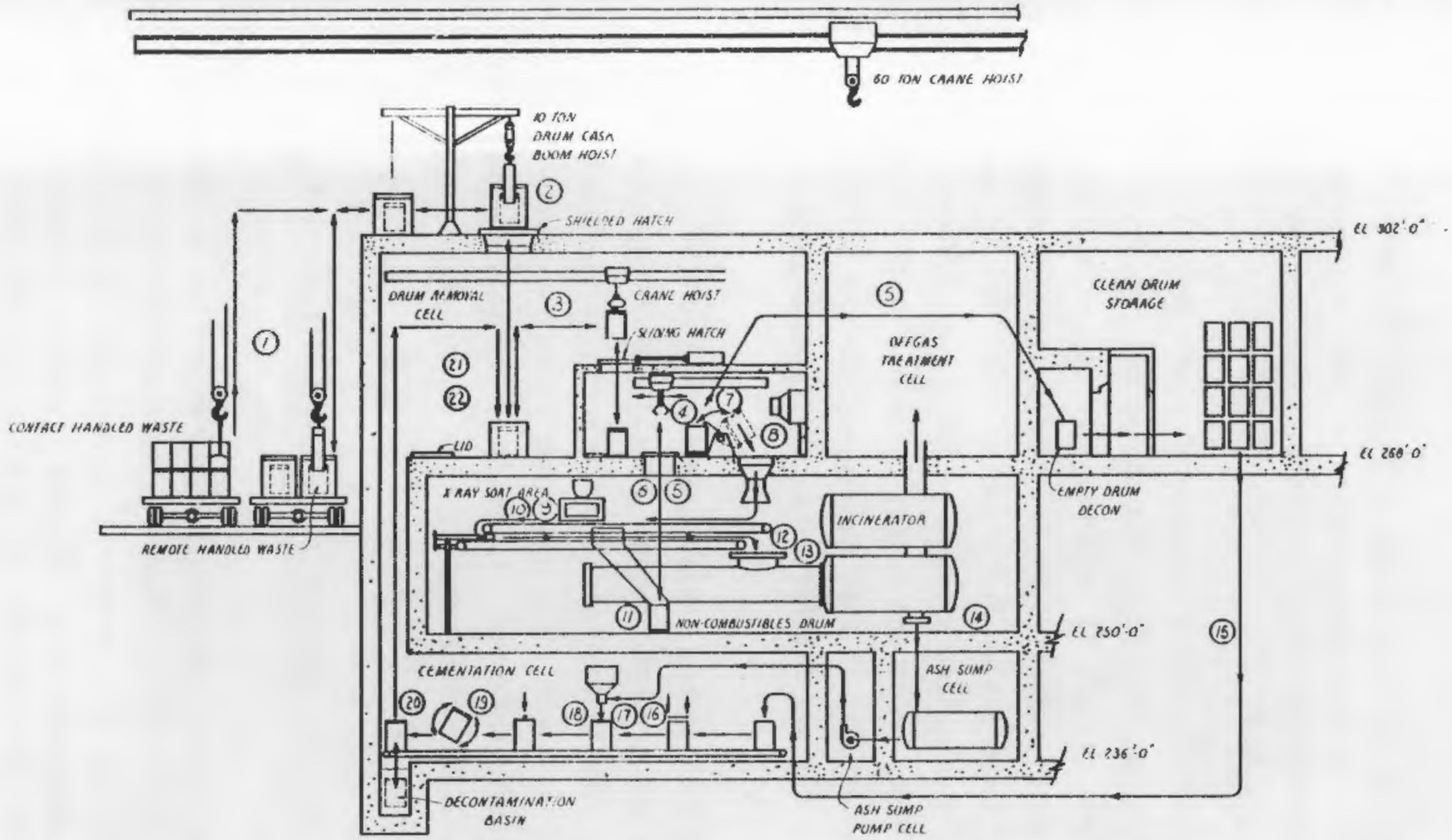
Incineration takes place in a dual chamber controlled air incinerator. The operation sequence envisioned in an early concept is shown in Figure B.30. Waste will be brought to the incineration facility by truck in 55- and 80-gal drums. The remote-handled drums will be encased in casks. The drums or casks would be unloaded from the truck and hoisted and positioned into the drum removal cell through the hatch above the cell. The drum would be transferred to the drum dumper, the drum lid would be removed and the waste would be dumped onto the momentum conveyor where it would pass an x-ray scanner in conjunction with master-slave manipulators for sorting out noncombustibles.

Combustible waste would be fed via a ram feeder to the combustion chamber where the waste materials are incinerated by a nonstoichiometric mixture of natural gas and air.

Noncombustibles would be placed in drums and sent for compaction if appropriate or to the repository for disposal.

Ash from the incineration operation would be gravity fed from the incinerator to the ash sump located in the ash sump cell directly below the incinerator. This remotely-operated tank would receive the ash as well as the off-gas scrubber solution concentrator bottoms.

The current concept for this waste treatment alternative differs from that described in Figure B.30 in several aspects. One, which was mentioned earlier, is that the wastes will be shredded prior to incineration. Another is that the filters and the noncombustible materials present in SAC waste will also pass through the incinerator. This means that the solid residue from incineration will contain shredded metal, filter media, and the ash produced by burning the combustible materials. A means of transferring this residue to the cementation



1. Move remote and/or contact handled waste drum or cask from truck to position on upper level adjacent to drum cask boom hoist via 60 ton crane hoist.
2. Move drum cask or drum thru shielded match to drum removal cell via drum cask boom hoist.
3. Using drum removal cell crane hoist, remove drum cask lid, move drum thru sliding hatch to drum dumper cell.
4. Using drum dumper cell crane hoist, move drum to position for drum dumper.
5. Move empty drum through guillotine door to position under noncombustibles chute and place bag in drum or send drum to decontamination and clean storage.
6. Move full drum of noncombustibles from under noncombustibles chute to drum dumper cell via the drum dumper cell crane hoist as required.
7. Using mechanical manipulators, remove drum lid and fasten drum in drum dumper.
8. Open chute plug and activate dumper.
9. Convey all trash to x-ray and rotate. Noncombustible item in bag will automatically stop the bat rotator and signal the operator.
10. Using manipulators, open bag and discard noncombustible drum.
11. When drum reaches desired level, close bag, lid drum, transport to noncombustible drum to the drum removal cell, load in cask for shipping.
12. Convey bagged waste to incinerator feed.
13. Feed waste into ignition chamber of incinerator with ram.
14. When waste is incinerated the ashes drop to wet ash slurry tank. Liquid from off-gas treatment is added. Wet ashes are sparged.
15. Remove empty drums from storage with use of elevator. Move to drum conveyor in cementation cell. Note: drums are to be fitted with bung hole lids.
16. Remove drum fill plug. Place a short piece of rebar inside drum with manipulator to agitate contents during mixing operation.
17. fill drum with a measured amount of cement at tare and solid mix weight scales.
18. Convey drum and plug to position under drum filling device. Add recirculated wet ash slurry to drum contents. Position and fasten fill plug.
19. Convey drum to drum mixer. Activate mixer.
20. Convey drum to smear test position. If surface radioactivity is detected, move drum by hoist via monorail to decontamination tank, then back to smear test position.
21. Using drum removal crane hoist, move drum up to drum removal cell and place in cask.
22. Reverse sequence 1-3.

FIGURE B.30. Operational Sequence for Incineration of Combustible Wastes process other than by pumping, as shown in Figure B.30, will therefore be required. The inclusion of SAC waste in the incinerator feed also means that provisions must be included of transferring this waste, which arrives at the WPF in 600-gal drums, to the shredder.

The off gas from the incinerator flows to a quench tower where it is cooled with dilute sodium hydroxide solution. The cooled off gas passes through a venturi scrubber where the gas is scrubbed with sodium hydroxide solution for particulate and acid removal, then to an acid absorber where the off gas is again contacted with the sodium hydroxide solution for NO_x and HCl removal. The treated off gas then passes through a cooler and de-entrainer. It is then heated to above the dew point and passed through a prefilter and a single-stage HEPA filter. The off gas is then exhausted into the building ventilation off-gas system for further filtration before release to the atmosphere.

Liquid wastes from the quench tower, the acid absorber, and the de-entrainer are collected in the scrubber recycle tank. Sodium hydroxide is added to the scrubber recycle tank to maintain the proper pH of the scrubber solution. The scrubber solution is collected and recycled to the quench tower, the venturi scrubber, and the acid absorber. Excess scrubber solution is transferred to the scrubber solution concentrator. The concentrator bottoms are sent to the cementation process.

B.4 DESCRIPTION OF WPF-4 (METALS MELTING PLUS INCINERATION/VITRIFICATION-ALTERNATIVE 4)

WPF-4 includes facilities to melt the metallic wastes and to incinerate the combustible wastes. The solid residue from the incineration process is segregated into a metallic portion and a portion that contains the ash from burning the combustibles plus the media from the HEPA filters. The metallic portion is melted with the other metallic wastes, and the ash plus media portion is used to provide some of the inert materials needed in the HLW vitrification process. These two portions were both cemented in the processes used in WPF-3. Cementation is also included in WPF-4 but only to immobilize the incinerator off-gas scrubber concentrate and some of the particulate solids. The compaction process that was part of WPF-3 is absent from WPF-4.

A general plot plan and arrangement for WPF-4 are shown in Figure B.31. The total capital cost for WPF-4 is estimated to be about $299 million and the operating cost is estimated to be $29.7 million/year.

B.4.1 Waste Vitrification in WPF-4

The waste vitrification facility and equipment for WPF-4 are slightly modified from that used in WPF-1, WPF-2, and WPF-3. Modifications are required to allow incinerator ash and filter media to be introduced to the ceramic melter units. The amounts of some of the glass-forming additives added as non-radioactive chemicals will also be reduced by the amounts of these materials present in the ash and filter media.

B.4.2 Waste Assay, Inspection, and Certification in WPF-4

The WAIC facility in WPF-4 will be very similar to that in WPF-1, WPF-2, and WPF-3. However, because of the smaller volume of treated waste, smaller post-certification storage facilities will be adequate for the desired storage period.

B.4.3 Waste Metals Melting in WPF-4

WPF-4 involves melting of all of the metallic wastes, instead of compaction or cementation as in WPF-3 (Section B.3) or compaction as in WPF-2 (Section B.2). Melting provides greater volume reduction and improved waste form stability than the processes discussed earlier.

B.4.3.1 Waste Metals Melting Facility

As shown in Figure B.31, the hulls and hardware (and other metals) melting (consolidation) process is located in the southwest quadrant of the facility adjacent to the solidification and incineration/cementation processes. The building and equipment layouts are shown in Figures B.32 through B.36.

The design of this portion of the WPF follows the general concept used in the other parts of this facility and includes provisions for receiving and shipping process materials, allowance for transferring materials to other processes as required, hot cells with support services and galleries for

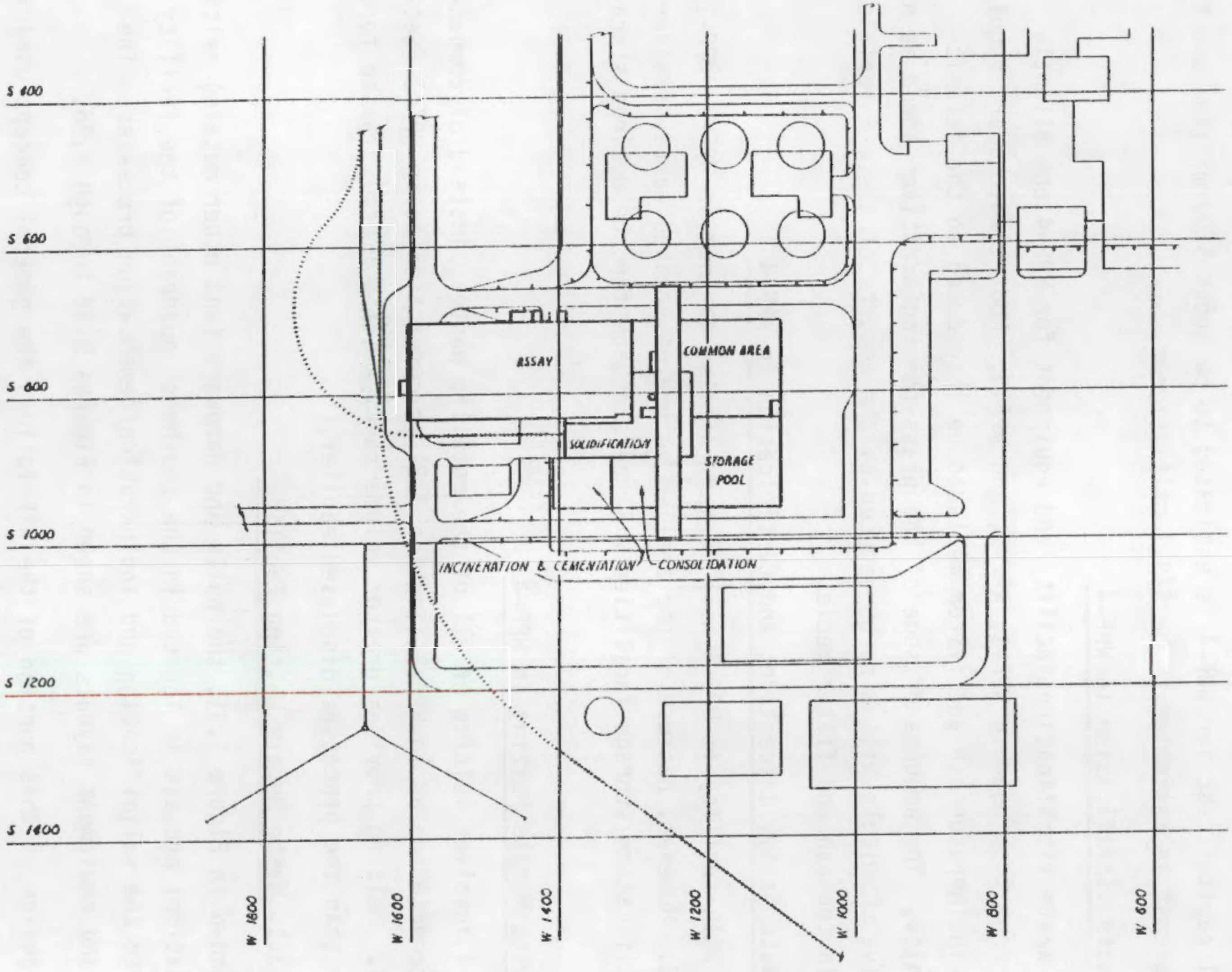


FIGURE B.31. Plot Plan for WPF-4

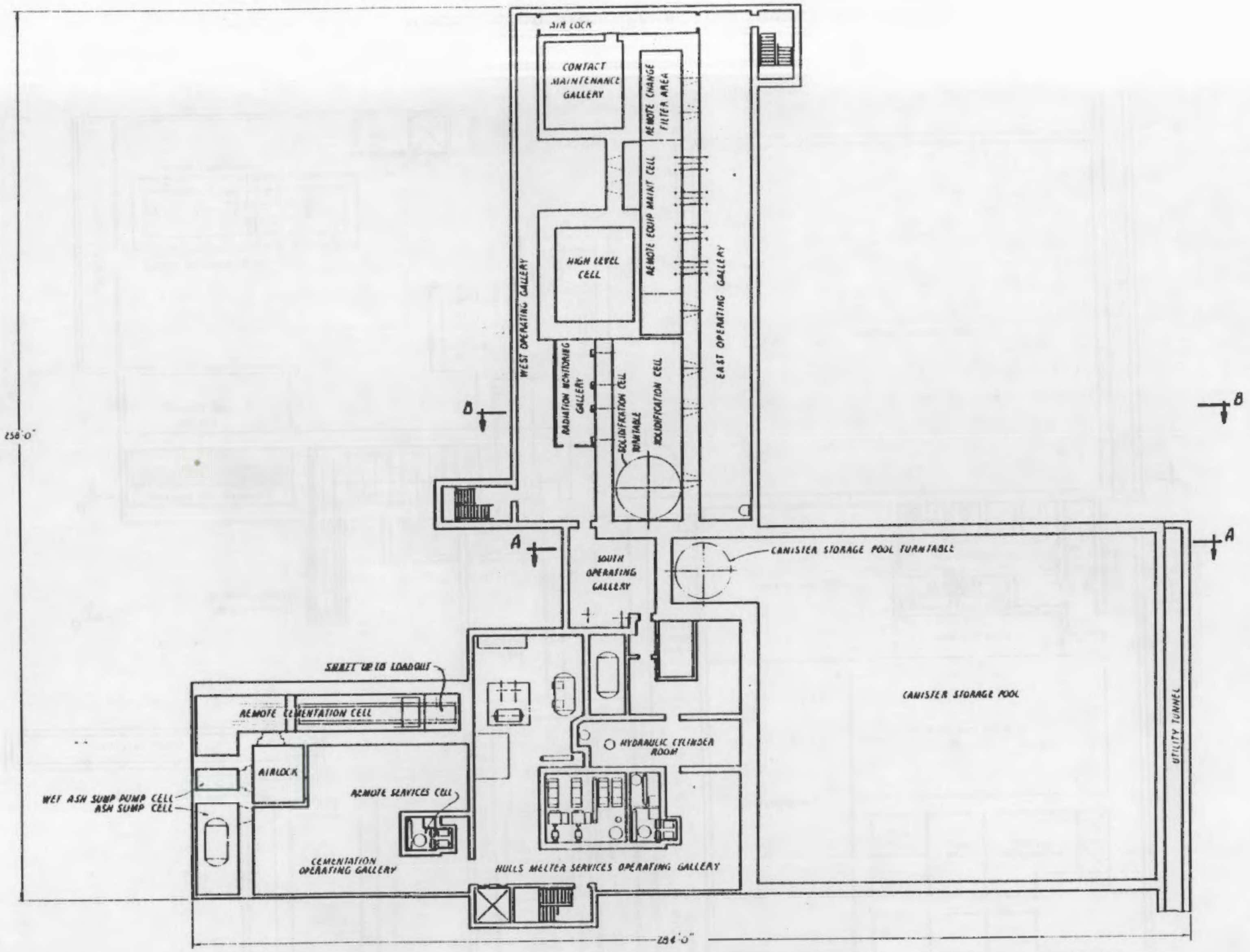


FIGURE B.32. Floor Plan for WPF-4 at Elevation 236'-0"

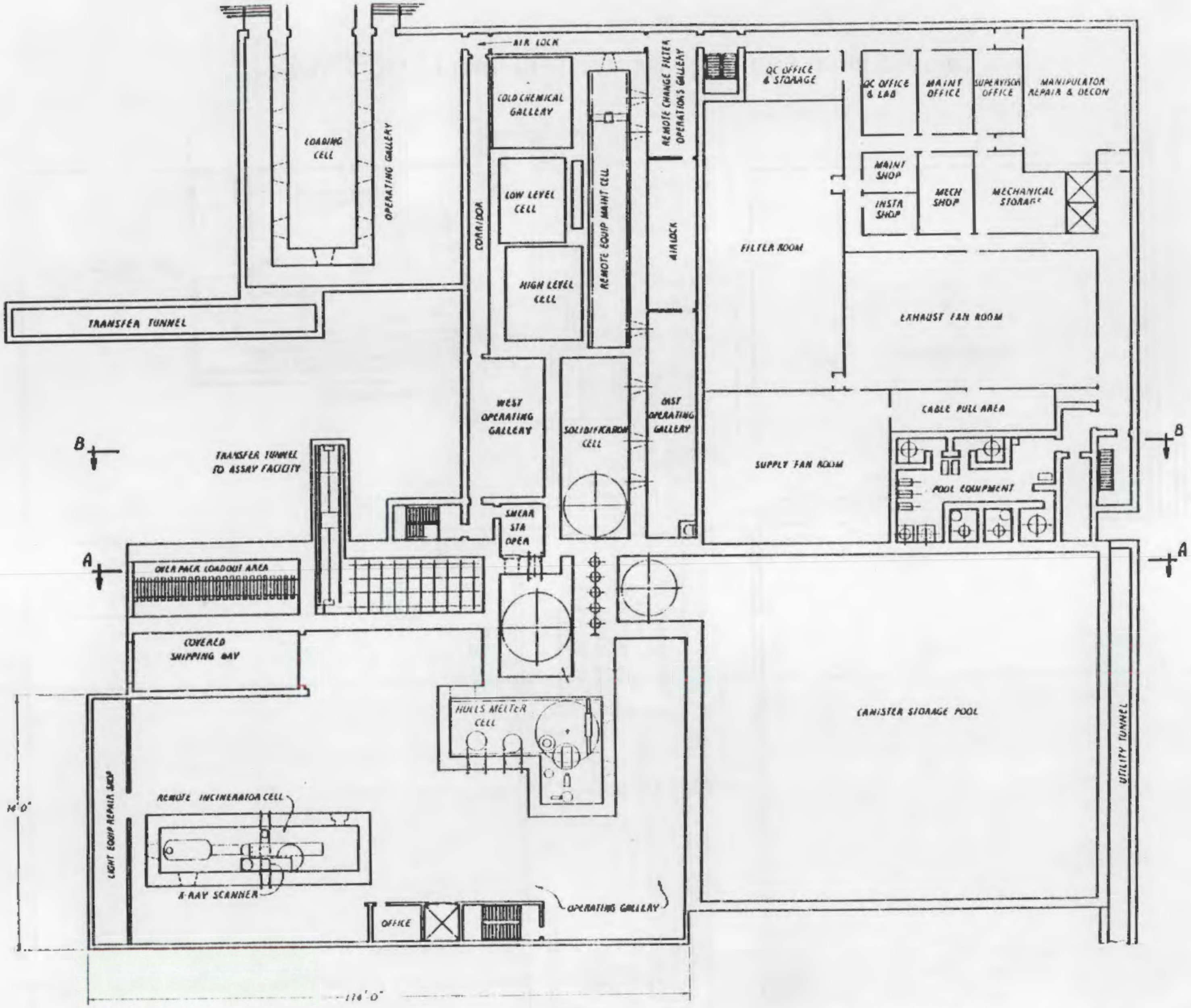


FIGURE B.33. Floor Plan for WPF-4 at Elevation 250'-0"

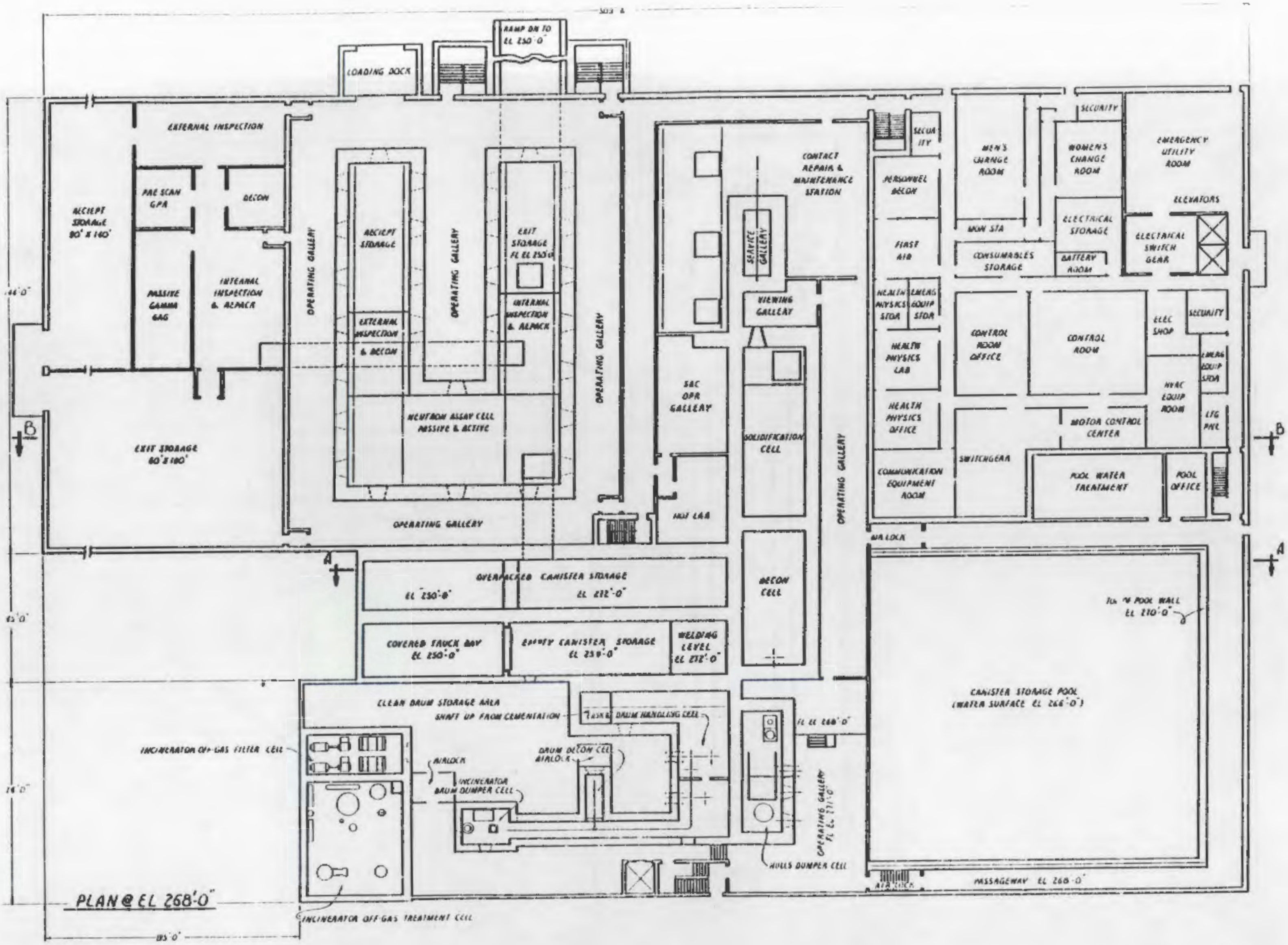


FIGURE B.34. Floor Plan for WPF-4 at Elevation 268'-0"

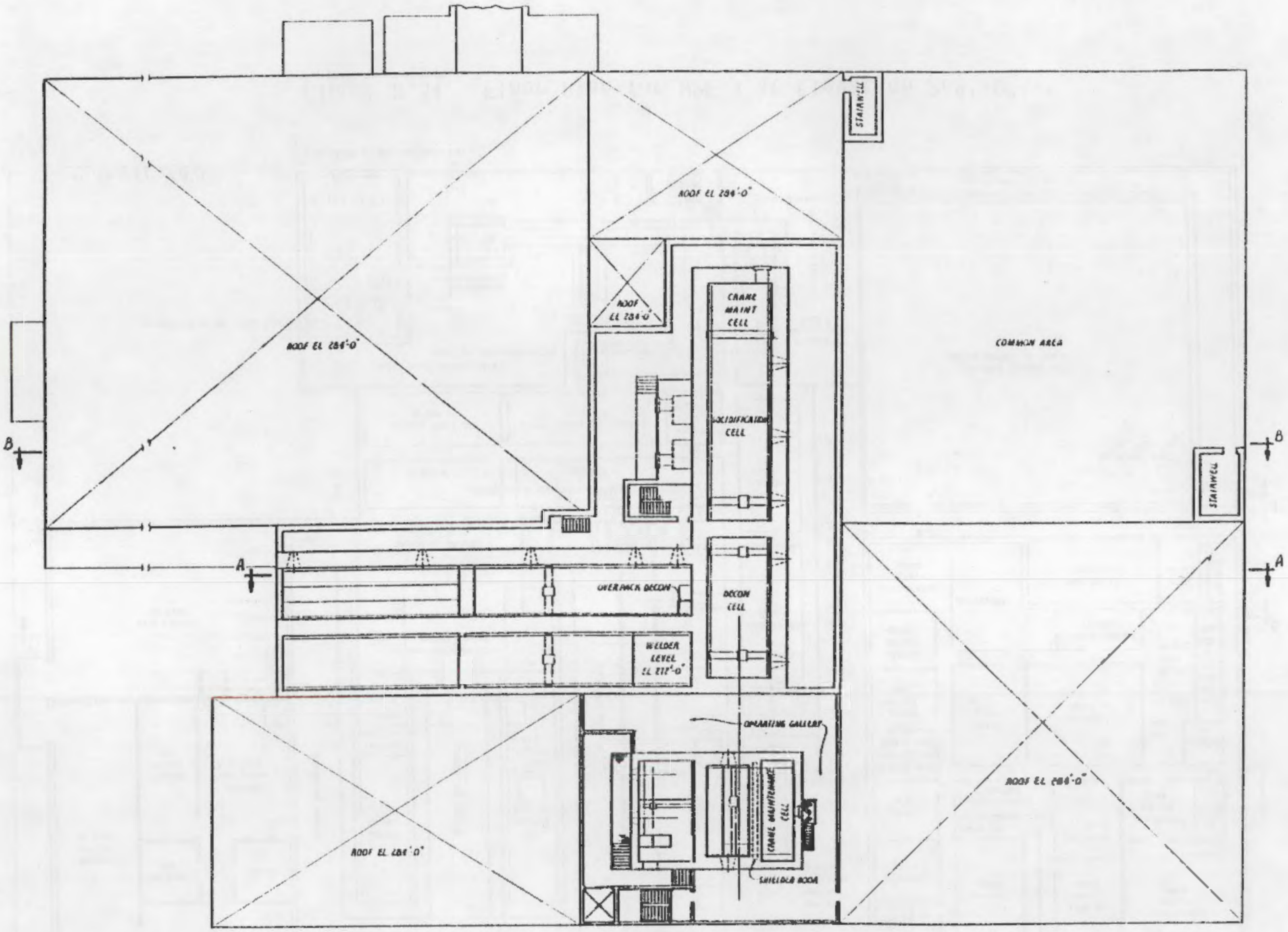


FIGURE B.35. Floor Plan for WPF-4 at Elevation 284'-0"

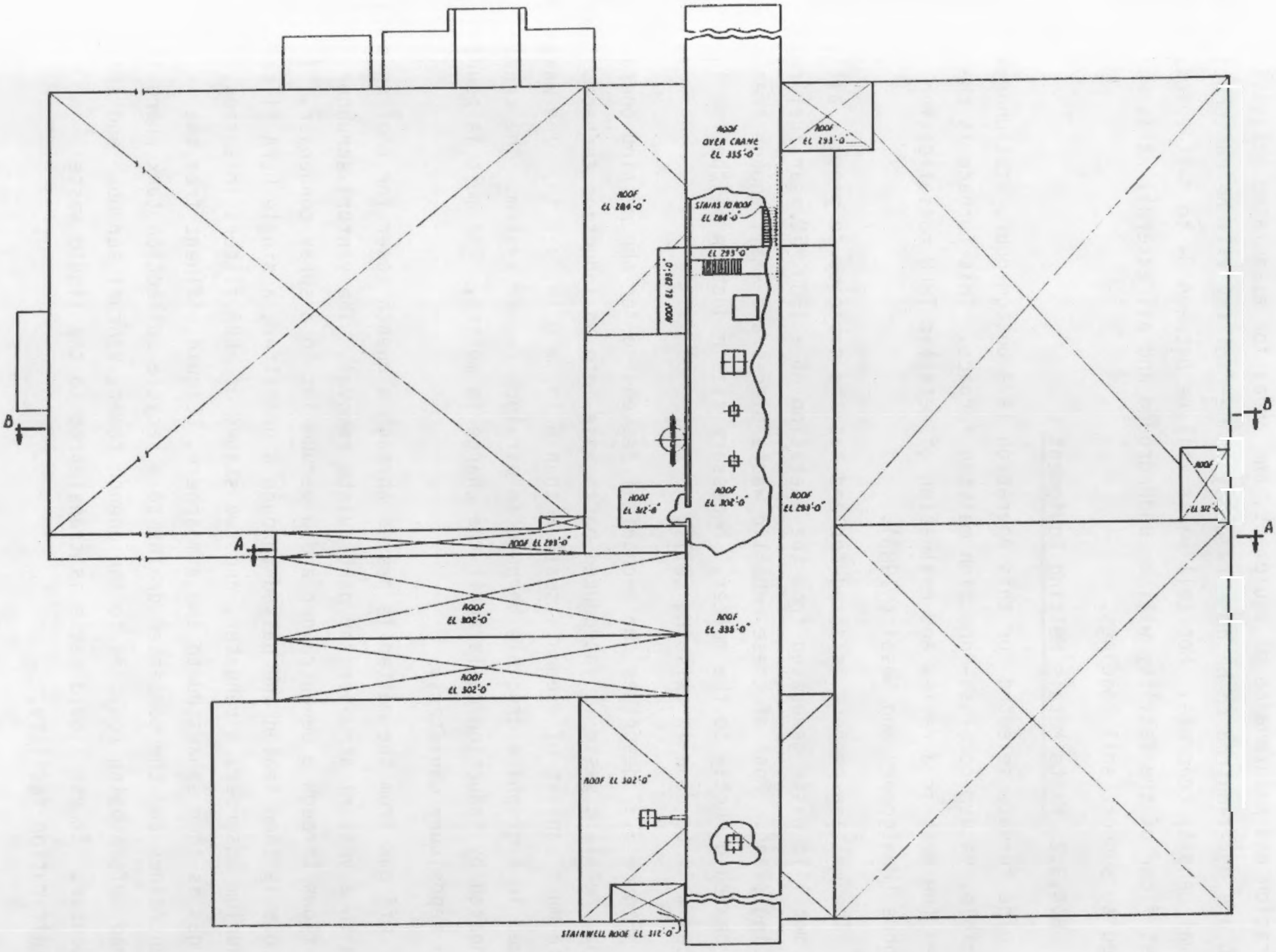


FIGURE B.36. Floor Plan for WPF-4 at Elevation 335'-0"

operation and maintenance of equipment, and areas for associated activities that are not required to be done remotely. The facility will be constructed of normal density concrete. Hot cell walls will be between 3- to 4-ft thick. The first floor of the facility will be underground and all external walls will be sized to support soil loadings.

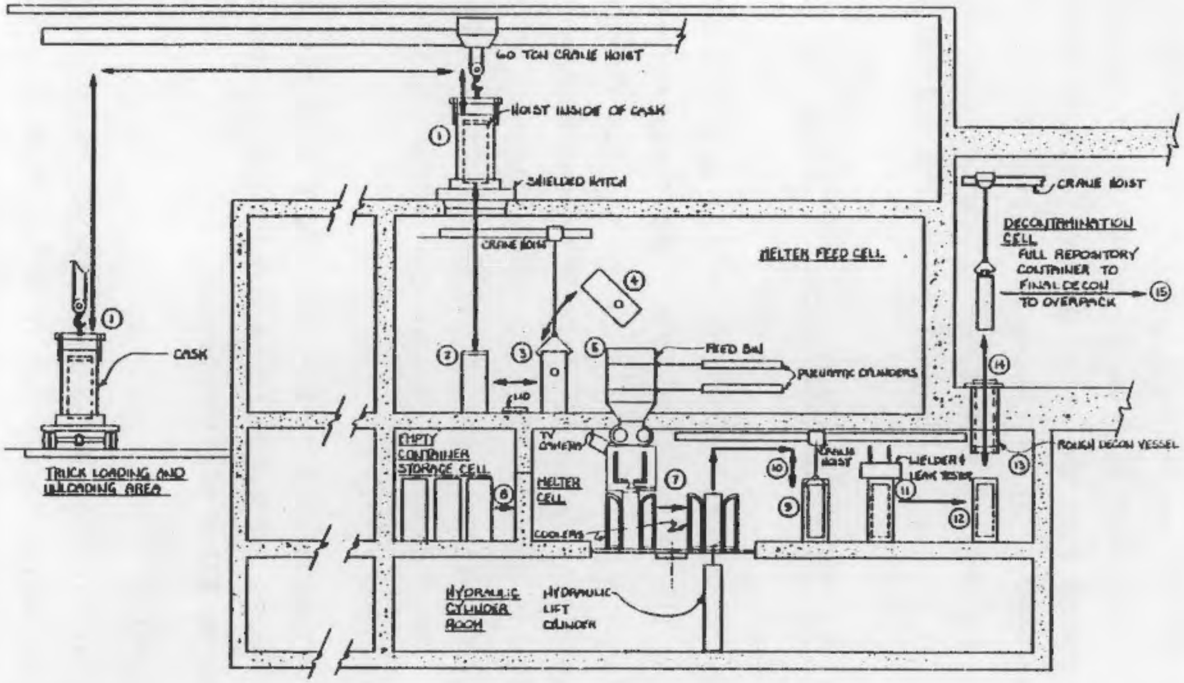
B.4.3.2 Waste Metals Melting Equipment

The furnace selected for this operation is a bottom-pour, stationary-crucible, vacuum-coreless-induction melting furnace. This furnace is the one rated the best in a review and evaluation of metallic TRUW consolidation methods (Montgomery and Nesbitt 1983).

The melting process is sized for and has the capacity to process all of the metallic waste generated from the operation of a 1500 MTU/year fuel reprocessing plant. Most of these metallic waste pieces are small enough that they can be fed directly to the melter. Necessary size reduction of the few larger pieces will be done in existing cells.

Figure B.37 describes the mechanical sequencing for the melting operation. Metallic waste is introduced batch wise into an induction furnace. The waste must consist of elements smaller than 6 in. x 6 in. x 6 in. The waste is placed in a graphite crucible through an air-lock feeder system. The crucible is heated by induction coils until the charge is melted. The melt is poured into repository canisters.

Off gas from the melter is passed through a quench tower for cooling and then to a venturi scrubber for particulate removal. The venturi scrubber off gas flows through a de-entrainer and a vacuum jet to a spray condenser. The off gas is then heated and passed through a prefilter, a single HEPA filter, a ruthenium adsorber, a reheater, and two stages of HEPA filters in series. The off gas is then exhausted to the atmosphere. Liquid effluent from the de-entrainer and the condenser drains to a recycle collection tank where it is stored before being recycled to the quench tower, venturi scrubber and spray condenser. Excess liquid waste is transferred to the liquid waste solidification facility.



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1. Move hulls and scrap metal cask from truck to shielded hatch on upper level via 60 ton crane hoist.
2. Lower container from inside cask to melter feel cell via hoist inside of hulls cask.
3. Move container to feed dumper via melter feel cell crane hoist.
4. Using mechanical manipulators, remove lid, position a fasten hopper adaptor.
5. Using melter feed cell crane hoist, transfer container contents to feed bin.
6. Reverse sequence of nos. 1 to 5 to return empty container to cask a cask to truck.
7. Metallic material is melted in furnace and poured into canister below. When canister is approximately 90% it is moved to cooling station via turntable and lift system.
8. Obtain empty repository container from storage. Insert empty container into melter cell thru empty repository container transfer drawer.
9. Move empty repository container to weld prep and canning position via the melter crane hoist.
10. Place helium source lid on repository container via lid transfer drawer. Weld lid in place and leak test.
11. Transfer full, sealed repository container to position under the rough decon vessel via the melter crane hoist.
12. Using decontamination cell crane hoist, lift full repository container into rough decon vessel, close vessel bottom hatch, release container inside vessel, remove crane hoist.
13. Close top match of rough decon vessel, activate vessel for desired period of time, drain vessel, open top match.
14. Using decon cell crane hoist, lift full repository container into the decontamination cell. Place into a repository overpack.

FIGURE B.37. Operational Sequence for Hulls Melting Process

B.4.4 Waste Incineration/Cementation in WPF-4

The waste incinerator/cementation facility in WPF-4 is slightly modified from that in WPF-3 (Section B.3.4). The modifications result from the fact that in WPF-4, some shredded metallic wastes (e.g., metal filter frames and metallic trash in SAC waste) are segregated from the other solid incinerator residues so that they can be melted with the other metallic wastes instead of being cemented as they were in WPF-3. As discussed in Section B.4.1, the other solid incinerator residues (e.g., ash and filter media) are transferred to the waste vitrification facility where they are immobilized in the HLW glass.

B.5 DESCRIPTION OF WPF-5 (METALS DECONTAMINATION PLUS INCINERATION/VITRIFICATION-ALTERNATIVE 5)

WPF-5 includes facilities to decontaminate most of the metallic wastes so that they can be disposed of as LLW rather than TRUW. The secondary wastes produced during decontamination are vitrified along with the HLW and the incinerator ash and filter media resulting from incineration of the combustible wastes. A cementation facility is also included for immobilization of the incinerator off-gas scrubber concentrate, some of the particulate solids, and some of the metallic wastes. WPF-5 does not contain the melter used in WPF-4 nor the compactor used in WPF-3 and WPF-2.

A general plot plan and arrangement for WPF-5 are shown in Figure B.38. The total capital cost for WPF-5 is estimated to be about $316 million and the operating cost is estimated to be $31.6 million/year.

B.5.1 Waste Vitrification in WPF-5

The waste vitrification facility for WPF-5 must produce roughly 1.5 times as much HLW glass as the vitrification facilities in WPF-1 through WPF-4. This condition results from the assumption used in this study that the secondary wastes produced during decontamination of the metallic wastes would be immobilized in the HLW glass. A large volume of glass is required to suitably immobilize the quantity of zirconium estimated to be removed during decontamination of the fuel hulls, and the aluminum oxide used as abrasive material. However,

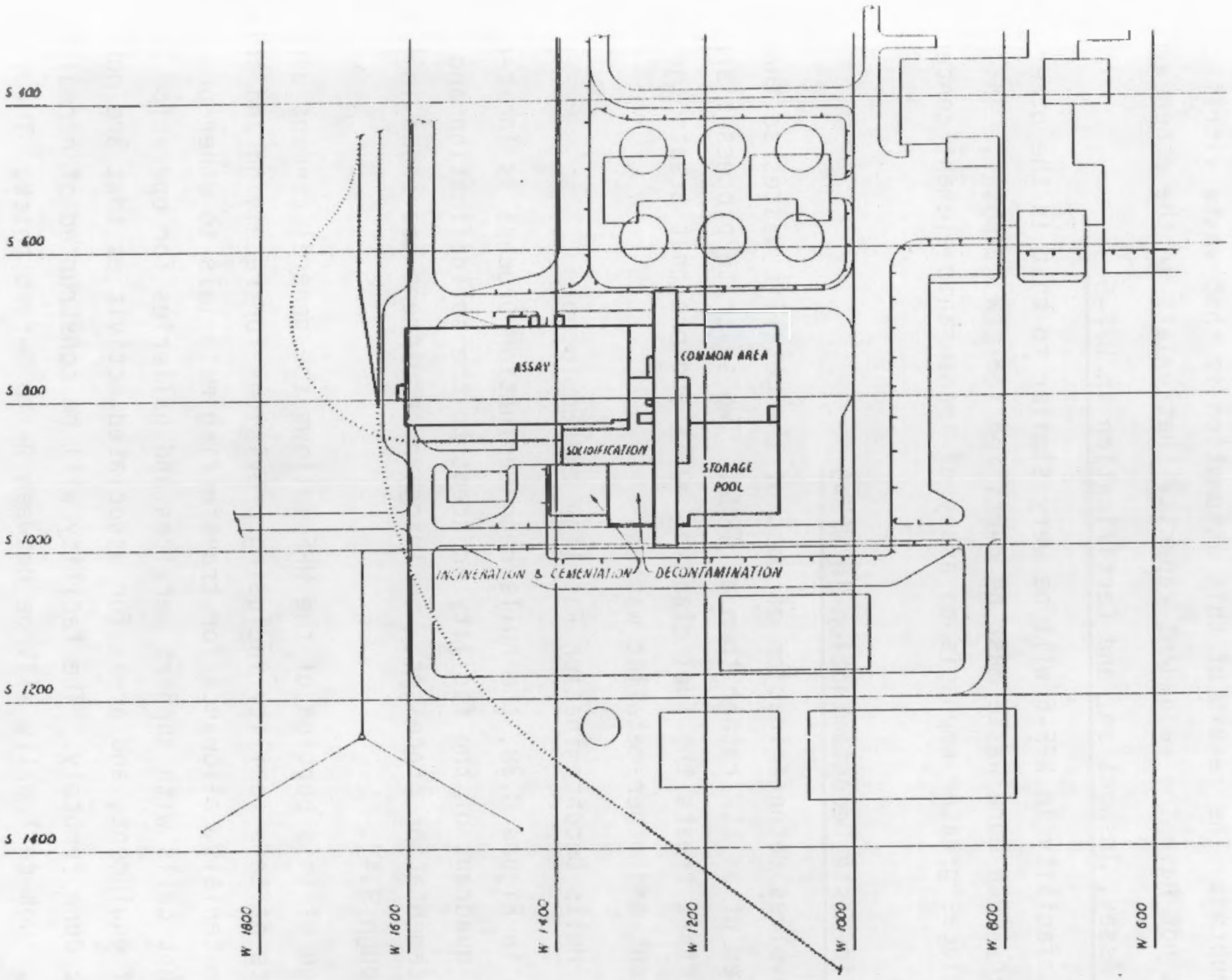


FIGURE B.38. Plot Plan for WPF-5

for this preliminary evaluation, we have assumed that the waste vitrification facility in WPF-5 will be essentially the same as in WPF-4, which contained two identical 100 percent capacity lines to assure that continuous operations would not be interrupted. The result of this assumption is that waste vitrification in WPF-5 does not have the redundant capacity that exists in the other WPFs.

B.5.2 Waste Assay, Inspection, and Certification in WPF-5

The WAIC facility in WPF-5 will be very similar to that in the other WPFs. However, much more waste must be certified for LLW disposal. This requirement places greater emphasis on assay of transuranic element content at lower levels.

B.5.3 Metallic Waste Decontamination in WPF-5

WPF-5 involves decontamination of most of the metallic wastes so that they can be disposed of as LLW rather than as TRUW. Two separate processes are employed, one that treats the fuel cladding hulls and one that treats the failed equipment and other metallic wastes.

B.5.3.1 Hulls Decontamination Facility and Equipment

As shown in Figure B.38, the hulls decontamination process is located in the southwest quadrant of the facility adjacent to the solidification and incineration/cementation processes. Building and equipment are shown in Figures B.39 through B.43.

The design of this portion of the WPF follows the general concept used in the other parts of this facility including provisions for receiving and shipping process materials, allowance for transferring materials to other processes as required, hot cells with support services and galleries for operation and maintenance of equipment, and areas for associated activities that are not required to be done remotely. The facility will be constructed of normal density concrete. Hot-cell walls will be between 3- to 4-feet thick. The first floor of the facility will be underground and all external walls will be sized to support soil loadings.

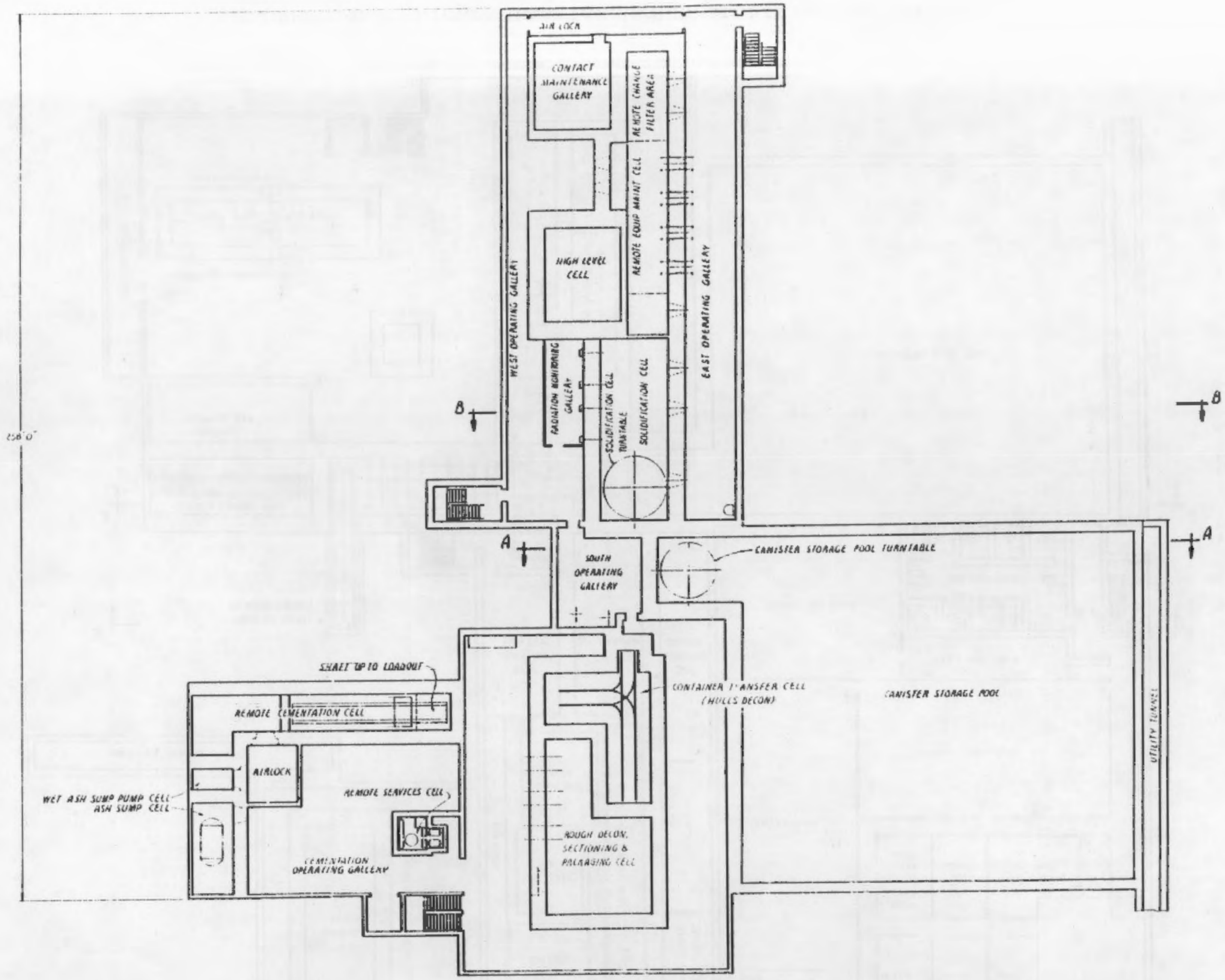


FIGURE B.39. Floor Plan for WPF-5 at Elevation 236'-0"

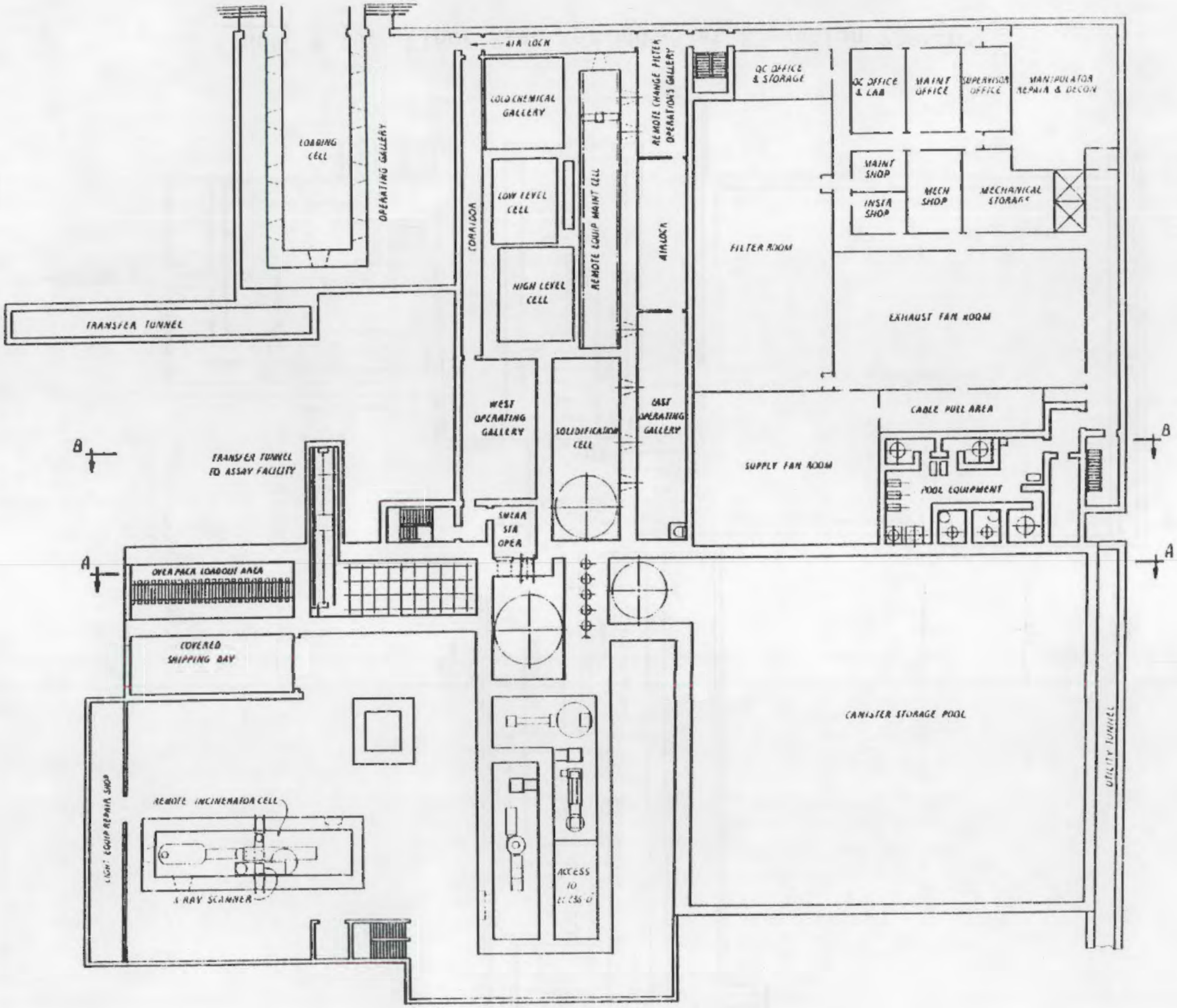


FIGURE B.40. Floor Plan for WPF-5 at Elevation 250'-0"

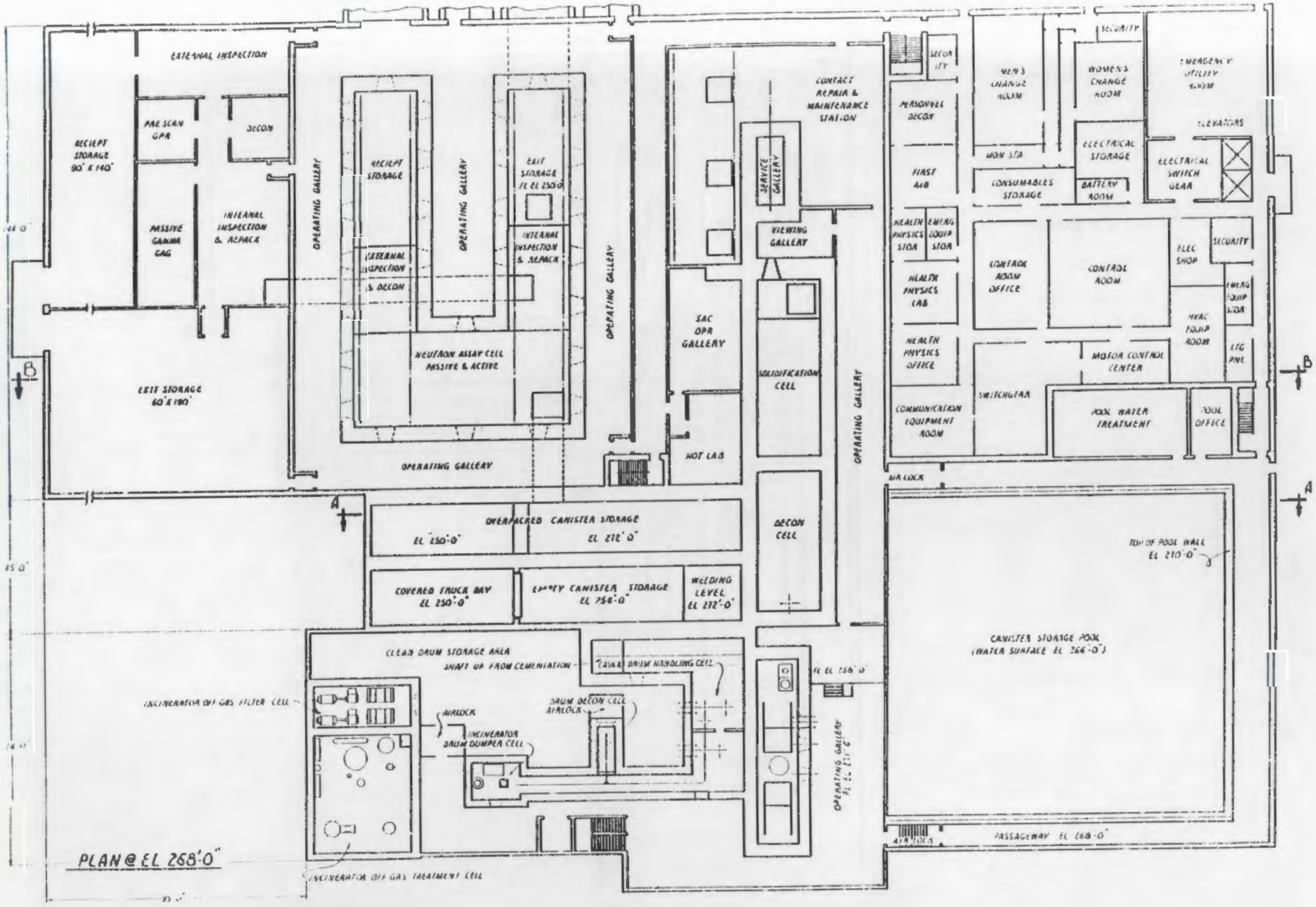


FIGURE B.41. Floor Plan for WPF-5 at Elevation 268'-0"

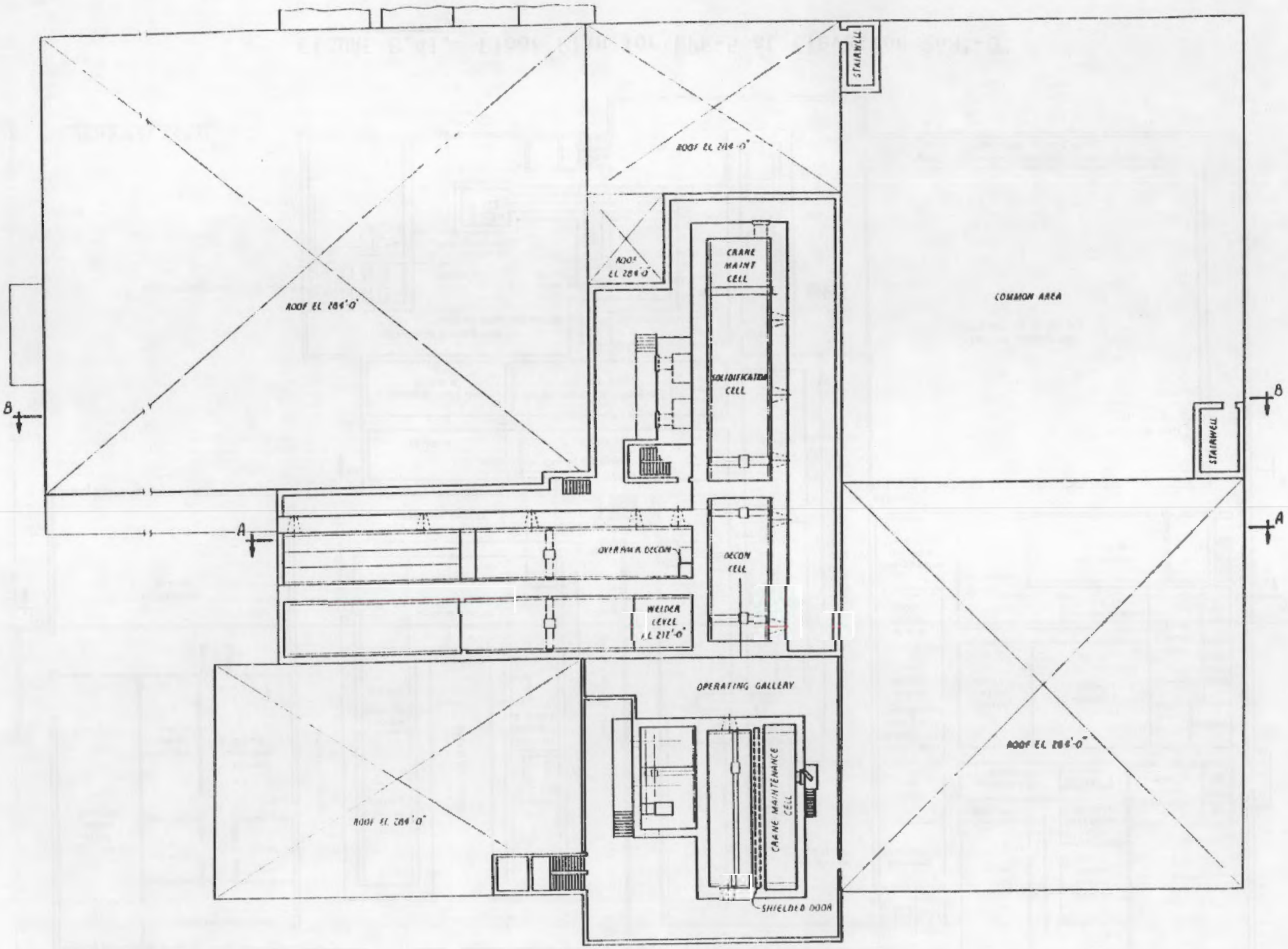


FIGURE B.42. Floor Plan for WPF-5 at Elevation 284'-0"

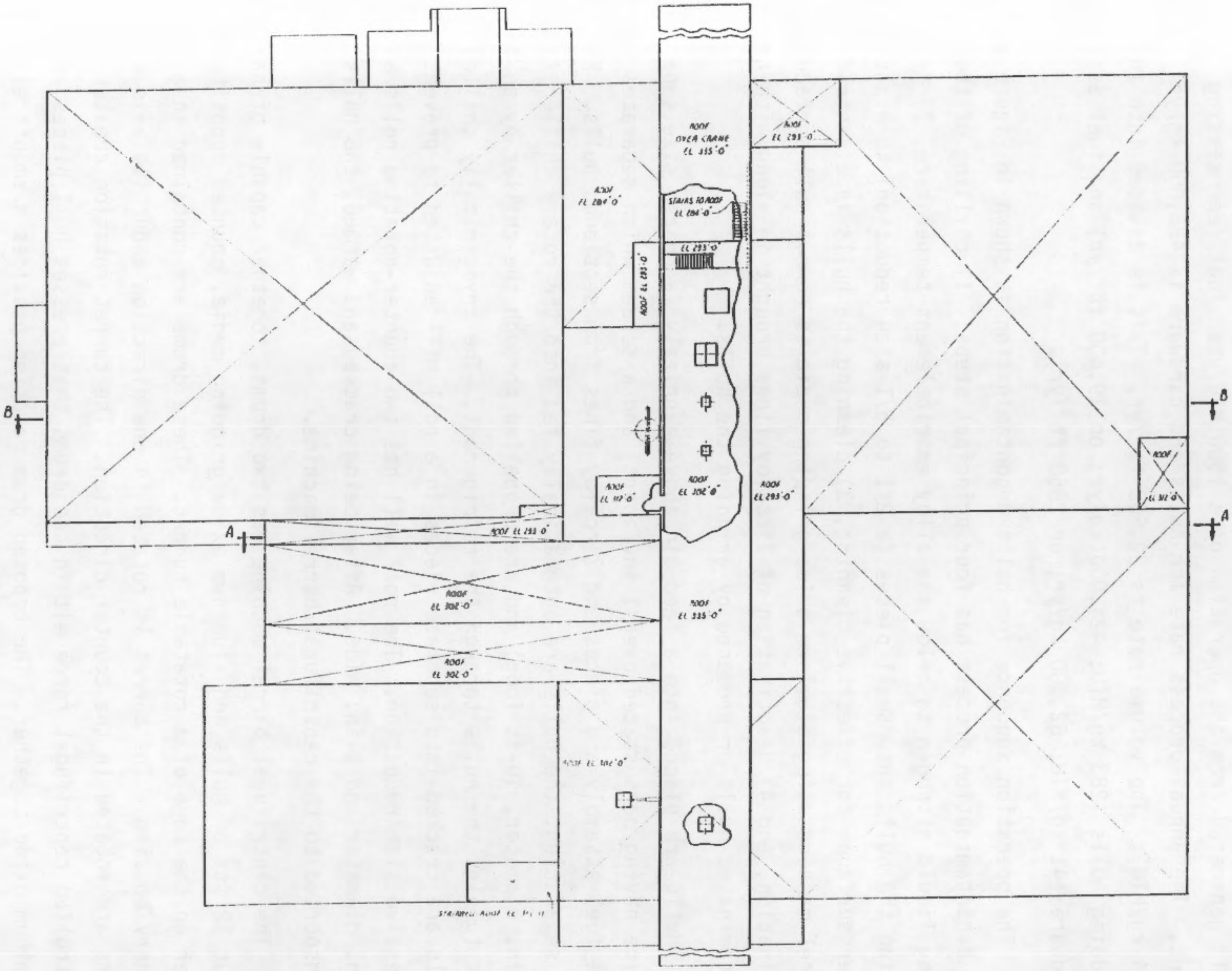


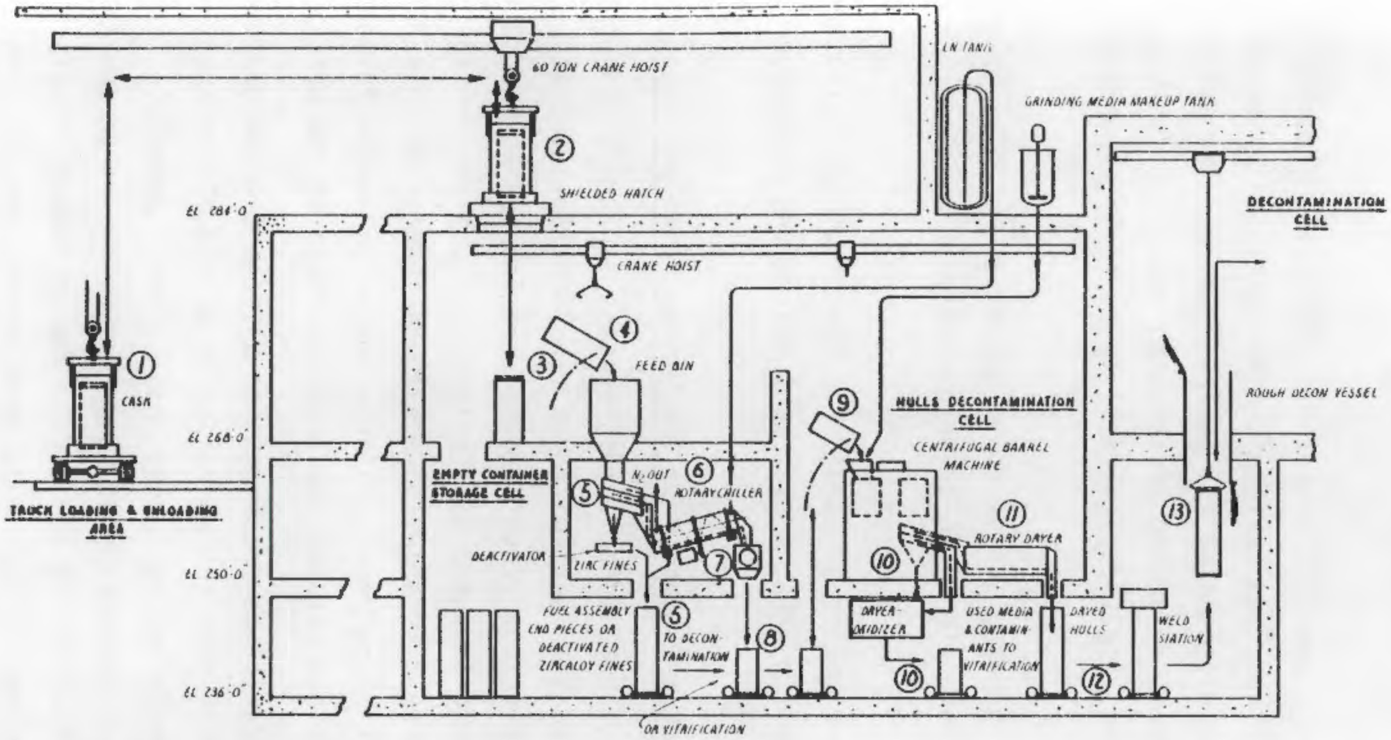
FIGURE B.43. Floor Plan for WPF-5 at Elevation 335'-0"

The decontamination process has the capacity to process all of the fuel hulls generated from the operation of a 1500 MTU/year fuel reprocessing plant. The annual process rate for hulls and hardware is 486,000 kg/yr (324 kg/MTU). The volume rate is 22,500 ft^3/yr. This is divided into fuel cladding hulls (283 kg/MTU; 424,000 kg/yr; or 19,600 ft^3/yr) and fuel assembly hardware (41 kg/MTU; 62,000 kg/yr; or 2850 ft^3/yr).

The operation sequence for hulls decontamination is shown in Figure B.44. The decontamination process has four principal steps: 1) chilling of the hulls using liquid nitrogen to below the alloy embrittlement temperature, 2) fracturing the hulls into small pieces (a 2/1 to 6/1 size reduction) to expose the inner surfaces for effective cleaning, 3) cleaning the hulls in a centrifugal barrel machine using aluminum oxide grinding media to remove hull surface contamination, and 4) deactivation of Zircaloy fines brought in along with the contaminated hulls or produced by grinding the hulls.

Hulls are placed into a feed bin above a grizzly (a coarse size separation device having bars spaced over 1 in. apart) and a screen which separates oversize fuel assembly and pieces and Zircaloy fines from sectioned hulls. Following separation, the hulls are automatically fed into the rotary chiller (about 24-in. diameter, 10-ft long) and are propelled through the chiller by an auger that tumbles the hulls through the refrigerant. The cryogenically chilled hulls are cracked into separate pieces in a roll mill adjusted to prevent excessive size reduction. The roll mill has two counter-rotating rolls about 9-in. diameter and 6-in. wide. After being cracked and warmed, the hulls are transported to the centrifugal barrel machine.

The centrifugal barrel machine has two drums, together capable of handling about 12 ft^3 of hulls and aluminum oxide grinding media, mounted opposite each other on the edge of a rotatable turret. These drums are contained in a stationary housing. The turret is rotated in one direction about its axis and the drums are rotated in the counter direction. The turret rotation creates a controlled centrifugal force within the drums that presses hull pieces and aluminum oxide together. The opposed drum rotation provides a smooth sliding action between the materials to remove contaminated surface to a controlled



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1. Move remote and/or contact handled waste drum or cask from truck to position on upper level adjacent to drum cask boom hoist via 60 ton crane hoist.
2. Move drum cask or drum thru shielded hatch to drum removal cell via drum cask boom hoist.
3. Using drum removal cell crane hoist, remove drum cask lid, move drum thru sliding hatch to drum dumper cell.
4. Dump container into feed bin.
5. Separate by size with grizzly and vibrating screen. Oversize material falls to container at elev 236'-0". Then transferred to vibratory finishing. Zircaloy fines go to deactivation: Deactivated material goes to container at elev 236'-0" and then transferred to vitrification. Hulls are transferred to rotary chiller feed hopper.
6. Hulls are chilled to cryogenic temperature using liquid nitrogen.
7. Chilled hulls are fractured in roll mill and transferred to container at elev 236'-0".
8. Hulls are brought to ambient temperature in container.
9. Container is transferred to decontamination cell (elev 250'-0") and dumped into centrifugal barrel machine. Grinding media is added and hulls are decontaminated.
10. Decontaminated hulls are dumped, rinsed, separated from fines and transferred to dryer. Rinsings and contaminated grinding media are dried, oxidized, and transferred to vitrification.
11. Hulls are dried with warm air and transferred to container (elev 236'-0").
12. Container is seal welded and leak checked.
13. Sealed container is externally decontaminated and transferred to decontamination cell.

FIGURE B.44. Operational Sequence for Hulls Decontamination Process depth. Normal process cycles for most industrial deburring applications are less than half an hour. Hulls decontamination times are anticipated to be about the same.

Following decontamination, the hull pieces are rinsed and screened to remove grinding media, hull fines, and surface contaminants. They are then dried, packaged, assayed, and disposed of as low-level waste. The mixture of grinding media and hull fines is dried and deactivated in a dryer/oxidizer unit and is then transferred to the vitrification facility to be incorporated in the HLW glass.

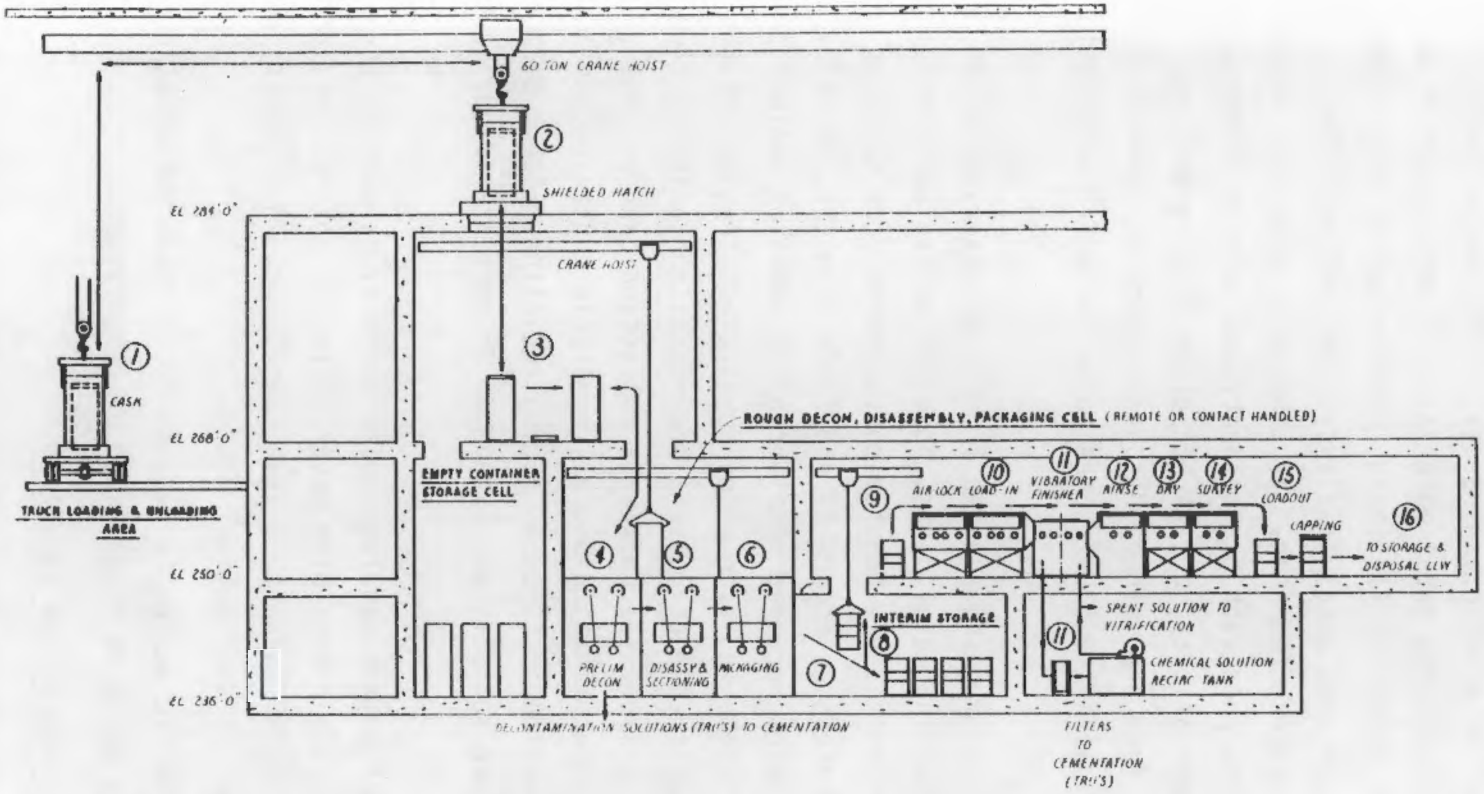
Oversize fuel assembly hardware is collected and decontaminated by vibratory finishing in the other metallic waste decontamination facility (Section B.5.3.2).

Off gas produced by vaporization of liquid nitrogen from the hulls decontamination process is sent to the WPF hot cell vent system and exhausted to atmosphere.

B.5.3.2 Failed Equipment and Other Metallic Wastes Decontamination

The facilities used to decontaminate failed process equipment and other metal wastes from TRU waste to low-level waste or from one low-level waste classification to a less restrictive classification are located on the south side of WPF-5. The arrangement of these facilities is also shown in Figures B.39 through B.43. Figure B.45 shows an elevation section of this portion of WPF-5 along with other cell arrangement information. The design follows the general design concepts described earlier for other portions of the WPF.

The facility has the capacity to decontaminate all the fuel hardware and the general process metal trash from the operation of a 1500 MTU/yr spent fuel reprocessing facility and the failed equipment that is small enough to fit in a 600-gal container. The annual production of these wastes can be processed through the decontamination facility in 300 days. The estimated annual throughput is 2750 ft^3 of segregated noncombustible general process trash, 2060 ft^3 of failed equipment, and 2850 ft^3 of fuel assembly hardware. The approach taken in this concept is to process both contact and remote-handled wastes separately but in the same facilities on campaign bases.



Vibratory Finisher System

1. Move remote and/or contact handled waste drum or cask from truck to position on upper level adjacent to drum cask boom hoist via 60 ton crane hoist.
2. Move container (cask or drum) thru shielded hatch to drum removal cell via drum cask boom hoist.
3. Using drum removal cell crane hoist, remove drum cask lid, move drum thru sliding hatch to decontamination, disassembly, packaging cell.
4. Unload container and person preliminary decontamination (contact or remote handling). Return container to empty container storage cell.
5. Perform disassembly or sectioning as needed (contact or remote handling).
6. Package disassembled or sectioned equipment.
7. And move to interim storage or
8. Decontamination (elev 250'-0").
9. Place container in airlock.
10. Unload container and
11. Place material into vibratory finisher and decontaminate. Chemical solution is filtered and recirculated.
12. Remove decontaminated material and rinse.
13. Dry and
14. Survey.
15. Load out decontaminated material into container, cap and send to disposal. Material not passing survey is returned to step 3.

FIGURE B.45. WPF-5 Section Showing Cell and Equipment Arrangement Details

A preliminary decontamination is performed in a glove-box type enclosure using water spray equipment or other cleaning devices to remove loosely adhered surface contaminants from the waste metal materials. Tightly adhered contaminants are removed later by vibratory finishing. Following the preliminary decontamination, the contaminated metal is disassembled and sectioned as necessary to fit within the vibratory finisher. Sectioning is done in a second glove-box type enclosure equipped with oxygen/acetylene cutting torches, plasma arc cutting torches, mechanical cutting saws, or other cutting devices. Contaminated waste solutions from preliminary decontamination or cleanup of the sectioning enclosure are solidified. Off gases go to the WPF-5 ventilation system.

The vibratory finishing process, adapted from a process used in the metal finishing industry for deburring metal parts, combines mechanical scrubbing and chemical action to remove the tightly adhered contaminants from surfaces of the sectioned metal parts. Processing occurs in a 5.25-ft diameter, 12 ft^3 vibrating, annular tub that contains hardened metal-grinding media of various shapes; the shape variations permit the media to enter corners and crevices of the waste. A chemical solution that both loosens and rinses contaminants from surfaces of the waste is recirculated between a collection tank and the vibrating tub. Most measurable contamination and all smearable contamination is removed. The chemical solution is filtered during recycling. Spent chemical solution is concentrated and solidified. Exhausted filters are immobilized by cementation.

After the separation from the metal grinding media by screening, the decontaminated metal parts are rinsed with water to remove any residue, dried, surveyed to ensure that the TRU content is less than 100 nCi/g of waste, packaged, assayed, and disposed of as low-level waste.

A fraction of the metallic wastes is assumed to be nondecontaminable by vibratory finishing. This waste is immobilized by cementation.

B.5.4 Waste Incineration/Cementation in WPF-5

The waste incineration/cementation facility in WPF-5 is slightly modified from that in WPF-4 (Section B.4.4) or in WPF-3 (Section B.3.4). The incinerator ash and filter media are segregated from the shredded metals that had passed through the incinerator and are immobilized in HLW glass, as in WPF-4. The shredded metals from the incinerator are cemented along with the incinerator off-gas scrubber concentrate and particulate solids as in WPF-3. Also immobilized by cementation in WPF-5 is the nondecontaminable portion of the noncombustible GPT and failed equipment.

B.6 APPENDIX B REFERENCES

AGNS. 1978. Studies and Research Concerning BNFP: Storage and Handling of Wastes from Uranium Fuel Processing Alternatives. AGNS-1040-3.3-34, Allied-General Nuclear Services, Barnwell, South Carolina.

Anderson, K. J. et al. 1979. Studies and Research Concerning BNFP: Engineering Evaluations of Waste Handling Services and Storage Facilities. AGNS-35900-4.2-26. Allied-General Nuclear Services, Barnwell, South Carolina.

Anderson, K. J. and T. A. Evans. 1983. An Evaluation of General Process Trash Disposal by Compaction. ONI/3141/RD-03, Allied-General Nuclear Services, South Carolina.

Barna, B. A. et al. 1983. Automated NDT Methods in Radioactive Waste Management. EEG-M-11883, EG&G Idaho, Idaho Falls, Idaho.

Brodzinski, R. L. et al. 1984. Design and Operation of a Passive Neutron Monitor for Assaying the TRU Content of Solid Wastes. PNL-4966, Pacific Northwest Laboratory, Richland, Washington.

Brodzinski, R. L. 1979a. "An Instrument for Determining the Transuranic Element Content of Chopped Leached Fuel Hulls and Other Material." Proceedings of 20th Annual Meeting I of NMM, 438.

Brodzinski, R. L. et al. 1979b. "An Instrument for Determining the Transuranic Element Content of Chopped Leached Fuel Hulls and Other Materials." PNL-SA-7548, Pacific Northwest Laboratory, Richland, Washington.

Brodzinski, R. L. and N. A. Wogman. 1978. In Situ Quantitative Determination of Transuranic Elements in Areas of High Level Gamma Radiation. NBS Special Publication 528, National Bureau of Standards, Washington, D.C.

Butcher, J. R. et al. 1980. Studies and Research Concerning BNFP: Report on Engineering Evaluation of Processing Alternatives. AGNS-35900-3.3-80. Allied-General Nuclear Service, Barnwell, South Carolina.

Caldwell, J. T. et al. 1983a. Test and Evaluation of a High Sensitivity Assay System for Bulk Transuranic Waste. LA-UR-83-2084, Los Alamos National Laboratory, Los Alamos, New Mexico.

Caldwell, J. T. et al. 1983b. Measurement of Radioactive Contaminated Wastes. LA-UR-83-307, Los Alamos National Laboratory, Los Alamos, New Mexico.

Caldwell, J. T. and W. E. Kunz. 1982. Experimental Evaluation of the Differential Dieaway Pulsed-Neutron Technique for the Fissile Assay of Hot Irradiated Fuel Waste. LA-UR-82-788, Los Alamos National Laboratory, Los Alamos, New Mexico.

Close, D. A., et al. 1983. Multi Isotopic Gamma Ray Assay System for Alpha Contaminated Wastes. LA-UR-83-1931, Los Alamos National Laboratory, Los Alamos, New Mexico.

Crane, T. W. 1980. Measurement of Uranium and Plutonium in Solid Waste by Passive Photon or Neutron Counting and Isotopic Neutron Source Interrogation. LA-8294-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.

Darr, D. G. 1983. Waste Model Characterization Study: Evaluation of Reprocessing Waste Estimates. AGNS, DOE/3156/FR-01, Allied-General Nuclear Services, Barnwell, South Carolina.

Kunz, W. E. 1983. "Differential Dieaway Technique Current Status of Los Alamos National Laboratory Work." In Proceedings of TRU Waste Assay Instrumentation Workshop, Los Alamos National Laboratory, Los Alamos, New Mexico.

Kunz, W. E., et al. 1981. A 1 mg-Sensitivity Fissile Assay System. LA-UR-81-1358, Los Alamos National Laboratory, Los Alamos, New Mexico.

Kunz, W. E. and J. T. Caldwell. 1982. Current Status of the Multi-Isotopic Transuranic Waste Assay System. LA-UR-82-787, Los Alamos National Laboratory, Los Alamos, New Mexico.

McKinley, K., et al. 1983. The Stored Waste Examination Pilot Plant at INEL. EEG-M-02083, EG&G Idaho, Idaho Falls, Idaho.

Montgomery, D. R. and J. F. Nesbitt. 1983. Review and Evaluation of Metallic TRU Nuclear Waste Consolidation Methods. PNL-4754, Pacific Northwest Laboratory, Richland, Washington.

Rogell, M. L., Steneck, P. D. 1983. Liquid Waste Solidification Facility - Detailed Design Criteria. AGNS PNL/3154/RD-04, Allied-General Nuclear Services, Barnwell, South Carolina.

Rogers, L. A., et al. 1983. "A Passive Neutron Counter for Determination of Transuranics in High Gamma Activity Samples." Proceeding IEEE Nuclear Science Symposium.

Slate, S. C., W. A. Ross, W. L. Partain. 1981. Reference Commercial High-Level Waste Glass and Canister Definition. PNL-3838, Battelle Pacific Northwest Laboratory, Richland, Washington.

Wogman, N. A. et al. 1978. An Instrument for Monitoring the Transuranic Content of Chopped Leached Hulls from Spent Nuclear Fuel Elements. NBS Special Publication 528, p. 284. National Bureau of Standards, Washington, D.C.

APPENDIX C

QUANTITIES OF TREATED WASTES

APPENDIX C

QUANTITIES OF TREATED WASTES

This section contains tables summarizing the quantities of treated wastes resulting from each of the waste treatment alternatives examined. For each alternative, the number of containers per 1500 MTU processed is tabulated by container size and surface dose rate for both LLW and TRUW. The total radionuclide content of each container of LLW is also listed, because this quantity also affects disposal costs. Table C.1 through C.5 contains the summaries for alternative treatment Alternatives 1 through 5a, and the summary for Alternatives 5b is in Table C.6.

To allow comparison of the long-term repository performance of the waste packages resulting from the various treatment alternatives, it was necessary to define the distribution of radionuclides among the treated TRUW packages. Table C.7 provides a means of determining this distribution; this table lists the fractions of radionuclides present in a portion of untreated waste that end up in a certain portion of treated waste. For example, in Alternative 2 the contact-handled, compacted waste contains 0.64 of the fission product activity that was initially present in the filters packaged within contact-handled 80-gallon drums, and the other 0.36 of the activity is present in the remote-handled compacted waste. The actual quantities of radionuclides present in the portions of untreated wastes are listed in Table A.6. Thus, multiplying the Ci/MTU values in Table A.6 by the fractions in Table C.7 leads to Ci/MTU values for the treated waste forms. Table 6.3 contains a summary comparison of such data for the examined treatment alternatives.

TABLE C.1. TRUW and LLW Containers for Package Without Treatment Alternative (Alternative 1)

Waste Classification	Container Surface Dose Rate, mR/hr	Container/1500 MTU (average Ci/container)		
		55-Gallon Drum	80-Gallon Drum	600-Gallon Canister
LLW-A	<50	13,318 (3.40×10^{-3})	86 (1.64×10^{-3})	19 (1.72×10^{-1})
LLW-B	<50	17 (9.48×10^{-2})	--	--
	50-100	--	--	6 (7.44×10^{-1})
	100-250	--	15 (1.96×10^{-1})	--
	250-500	--	5 (6.13×10^{-1})	--
		17	20	6
LLW-C	<50	1,097 (5.51×10^{-2})	54 (5.67×10^{-2})	--
	50-100	46 (4.34×10^{-1})	--	14 (7.82×10^{-1})
	100-250	120 (1.99×10^{-1})	7 (1.96×10^{-1})	--
	250-500	281 (1.30)	2 (6.13×10^{-1})	3 (3.35)
		1,544	63	17
Total LLW		14,879	169	42
TRUW-CH	<200	660	1114	4
TRUW-RH	$200-10^3$	198	108	29
	10^3-10^4	93	25	8
	10^4-10^5	--	--	9
	10^5-10^6	--	--	39
	10^6-10^7	--	--	300
		291	133	385
Total TRUW		951	1,247	389
Total LLW and TRUW		15,830	1,416	431

TABLE C.2. TRUW and LLW Containers for Compaction Alternative (Alternative 2)

Waste Classification	Container Surface Dose Rate, mR/hr	Container/1500 MTU (average Ci/container)		
		55-Gallon Drum(a)	80-Gallon Drum(b)	600-Gallon Canister(a)
LLW-A	<50	4043 (1.96×10^{-3})	1138 (3.29×10^{-2})	19 (1.72×10^{-1})
LLW-B	<50	17 (9.48×10^{-2})	--	--
	50-100	--	--	6 (7.44×10^{-1})
	250-500	--	0.1 (9.95×10^{-1})	--
	1000-5000	--	1.0 (5.71)	--
		17	1	6
LLW-C	50-100	46 (4.34×10^{-1})	49 (2.47×10^{-1})	10 (9.52×10^{-1})
	100-250	--	86 (6.18×10^{-1})	3 (3.35)
	250-500	281 (1.30)	2 (1.36)	--
	500-1000	--	10 (2.07)	--
	1000-5000	--	1 (2.54)	--
		327	148	13
Total LLW		4387	1287	38
TRUW-CH	<200	70	63	4
TRUW-RH	$200-10^3$	93	43	1
	10^3-10^4	--	42	2
	10^4-10^5	--	15	1
	10^5-10^6	--	2	--
	10^6-10^7	--	1	--
	$>10^7$	--	361	--
		93	464	4
Total TRUW		163	527	8
Total LLW and TRUW		4550	1814	46

(a) All of these wastes are untreated.
(b) All of these wastes are compacted.

TABLE C.3. TRUW and LLW Containers for Incineration/Cementation Plus Compaction Alternative (Alternative 3)

Waste Classification	Container Surface Dose Rate, mR/hr	Container/1500 MTU (average Ci/container)		
		55-Gallon Drum(a)	80-Gallon Drum(b)	600-Gallon Canister(a)
LLW-A	<50	216 ([illegible] × 10^{-5}) [CM]	402 (1.76 × 10^{-2})	19 (1.72 × 10^{-1})
		1043 (1.96 × 10^{-3})	--	--
		1259	402	19
LLW-B	<50	17 (9.18 × 10^{-2})	--	--
	50-100	--	--	6 (7.44 × 10^{-1})
LLW-C	<50	92 (2.44 × 10^{-1}) [CM]	--	--
	50-100	500 (7.30 × 10^{-1}) [CM]	49 (2.47 × 10^{-1})	10 (9.52 × 10^{-1})
	100-250	--	5 (9.59 × 10^{-1})	3 (3.35)
		592	54	13
Total LLW		1868	456	38
TRUW-CH	200	70	16	4
		15 [CM]	--	--
		85	16	4
TRUW-RH	200-10^3	173 [CM]	12	1
	10^3-10^4	62 [CM]	4	2
	10^4-10^5	3 [CM]	--	1
	10^5-10^6	161 [CM]	--	--
	>10^6	--	354	--
		399	370	4
Total TRUW		484	386	8
Total LLW and TRUW		2352	842	46

(a) These wastes are untreated except for those denoted [CM], which are cemented.
(b) All of these wastes are compacted.

TABLE C.4. TRUW and LLW Containers for Metal Melting Plus Incineration/ HLW Vitrification Alternative (Alternative 4)

Waste Classification	Container Surface Dose Rate, mR/hr	Container/1500 MTU (average Ci/container)	
		55-Gallon Drum[a]	160-Gallon Canister[b]
LLW-A	<50	368 (~1 x 10^{-5}) [CM]	--
		4035 (1.91 x 10^{-3})	
		4403	
LLW-B		--	--
LLW-C	<50	82 (2.44 x 10^{-1}) [CM]	--
	50-100	500 (7.30 x 10^{-1}) [CM]	--
		582	
Total LLW		4985	--
TRUW-CH		--	--
TRUW-RH	200-10^3	166 [CM]	--
	>10^7	--	170
Total TRUW		166	170
Total LLW and TRUW		5151	170

(a) Cemented wastes denoted by [CM]; other waste is untreated.
(b) Melted metals.

TABLE C.5. TRUW and LLW Containers for Metals Decontamination Plus Incineration/HLW Vitrification Alternative (Alternative 5a)

Waste Classification	Container Surface Dose Rate, mR/hr	Container/1500 MTU (average Ci/container)	
		55-Gallon Drum(a)	160-Gallon Canister
LLW-A	<50	160 (~1 x 10^{-5})	--
		4035 (1.91 x 10^{-3}) [U]	
		1643 (8.34 x 10^{-3}) [D]	
		5838	
LLW-B	<50	4 (9.72 x 10^{-2})	--
	100-250	21 (6.38 x 10^{-2})	--
		25	
LLW-C	<50	169 (1.47 x 10^{-1})	--
	50-100	570 (7.45 x 10^{-1})	--
	250-500	10 (2.97 x 10^{-1})	--
	~7 x 10^4	--	504(b)
	~2 x 10^7	--	153(b)
		749	657
Total LLW		6612	657
TRUW-CH	<200	178	--
TRUW-RH	200-10^3	184	--
	10^3-10^4	17	--
	10^4-10^5	6	--
	10^5-10^6	11	--
		218	--
Total TRUW		396	--
Total LLW and TRUW(c)		7008	657

(a) These wastes are cemented except for that denoted [U], which is untreated, and that denoted [D], which are metallic wastes that were decontaminated to (or were initially) this level.

(b) These wastes are packaged in high integrity containers (HICs).

(c) In addition to the containers listed here, this treatment option results in an increase of 362 HLW canisters.

TABLE C.6. TRUW and LLW Containers for Incineration/TRUW Vitrification Option of Metals Decontamination Alternative (Alternative 5b)

Waste Classification	Container Surface Dose Rate, mR/hr	Container/1500 MTU (average Ci/container)	
		55-Gallon Drum(a)	160-Gallon Canister
LLW-A	<50	264 (~1 x 10^{-5})	--
		4035 (1.91 x 10^{-3}) [U]	
		1643 (8.34 x 10^{-3}) [D]	
		5838	
LLW-B	<50	4 (9.72 x 10^{-2})	--
	100-250	21 (6.38 x 10^{-2})	--
		25	
LLW-C	<50	169 (1.47 x 10^{-1})	--
	50-100	570 (7.45 x 10^{-1})	--
	250-500	10 (2.97 x 10^{-1})	--
	~7 x 10^4	--	504(b)
	~2 x 10^7	--	153(b)
		749	657
Total LLW		6716	657
TRUW-CH		--	--
TRUW-RH	10^4-10^5	--	6(c)
	10^6-10^7	--	184(d)
Total TRUW		--	190
Total LLW and TRUW		6716	847

(a) These wastes are cemented except for that denoted [U], which is untreated, and that denoted [D], which are metallic wastes that were decontaminated to (or were initially) this level.

(b) These wastes are packaged in HICS.

(c) Melted metals.

(d) TRUW glass.

TABLE C.7. Distribution of Input Radionuclides Among Different TRUW Forms for the Treatment Alternative

Treatment Alternatives	Waste Form	Hulls and Hardware	Filters				GPT		SAC	Failed Equipment		Fluorinator Solids
			CH		RH							
			55-gal	80-gal	80-gal	600-gal	CH	RH		CH	RH	
1	Untreated Waste											
	CH	--	1.0	1.0	--	--	1.0	--	--	1.0	--	--
	RH	1.0	--	--	1.0	1.0	--	1.0	1.0	--	1.0	1.0
2	Untreated Waste											
	CH	-	--	--	--	--	--	--	--	1.0	--	--
	RH	-	--	--	--	--	--	--	--	--	1.0	1.0
	Compacted Waste											
	CH	-	1.0	0.64(c)	--	--	--	--	--	--	--	--
	RH	1.0	--	0.35(c)	1.0	1.0	1.0(d)	1.0	1.0	--	--	--
3	Untreated Waste											
	CH	--	--	--	--	--	--	--	--	1.0	--	--
	RH	--	--	--	--	--	--	--	--	--	1.0	1.0
	Compacted Waste											
	CH	--	--	--	--	--	0.0(e)	--	--	--	--	--
	RH	1.0	--	--	--	--	0.20(e)	0.20	--	--	--	--
	Cemented Waste											
	RH	--	1.0	1.0	1.0	1.0	0.80	0.80	1.0	--	--	--
4	Melted Waste											
	CH	--	--	--	--	--	--	--	--	--	--	--
	RH	1.0	0.33	0.28	0.17	0.33	0.20	0.20	0.40	1.0	1.0	--
	Cemented Waste											
	RH	--	--	--	--	--	--	--	--	--	--	1.0
	In HLW Glass	--	0.67	0.72	0.83	0.57	0.80	0.80	0.60	--	--	--
5a	Cemented Waste											
	CH	--	0.33	0.28	--	--	0.06	--	--	0.30	0.30	--
	RH	--	--	--	0.17	0.33	--	0.06	0.40	--	--	1.0
	In HLW Glass	1.0(f)	0.67	0.72	0.83	0.67	0.94	0.94	0.60	0.70	0.70	--
	In LLW	0.0(f)	--	--	--	--	--	--	--	--	--	--
5b	Melted Waste											
	RH	--	0.33	0.28	0.17	0.33	0.06	0.06	0.40	0.30	0.30	--
	TRUW Glass											
	RH	1.0(f)	0.67	0.72	0.83	0.67	0.94	0.94	0.60	0.70	0.70	1.0
	In LLW	0.0(f)	--	--	--	--	--	--	--	--	--	--

(a) Fraction applies to all contained radionuclides unless otherwise indicated.
(b) See Table A.6 for the quantities of radionuclides in the initial wastes.
(c) Transuranic distribution is 0.22 CH and 0.78 RH.
(d) Transuranic distribution is 0.24 CH and 0.76 RH.
(e) Transuranic distribution is 0.05 CH and 0.15 RH.
(f) Activation product distribution is 0.07 to glass and 0.93 to LLW.

APPENDIX D

ACTINIDE SOLUBILITIES IN REPOSITORY ENVIRONMENTS

APPENDIX D

ACTINIDE SOLUBILITIES IN REPOSITORY ENVIRONMENTS

In this appendix, actinide solubilities in repository environments are formulated based on extensive work done at PNL and also on other work reported in the literature. The objective is to provide reasonable estimates of the solubilities of actinides under more or less generic nuclear waste repository conditions based on reasonably reliable available data and means of estimation. It is recognized, most importantly, that the environments of such a repository or repositories may be either oxidizing or reducing. For example, a repository in tuff might exhibit oxidizing conditions; whereas, a repository in basalt would definitely have reducing conditions. It is also recognized that the conditions in a repository might be highly saline, as in a salt repository, or nonsaline. Beyond these divisions there has not been any attempt to be site specific. This study should not be considered comprehensive but does treat factors of importance to estimation of actinide solubilities and, as such, is a guide to solubilities of actinides as well as to gaps in our information on solubilities.

D.1 GENERAL BASES FOR VALUES

Overall, the treatment of actinide solubilities has been conservative. Thus, for example, in cases where it can be anticipated that the stable phase might be a tetravalent oxide, it is generally assumed that the hydrous (amorphous) oxide prevails rather than the fully crystalline oxide even though the latter are certainly considerably less soluble. There is considerable evidence, at PNL and elsewhere, that in the case of the tetravalent metals, the fully crystalline oxides are more stable than the hydrous oxides by from 9 to 13 kcal/mole. Thus, a value for the free energy of formation of hydrous oxide can be determined from its solubility product. Comparison of these values for Th, Np, and Pu to values for the crystalline dioxides determined from the data of Fuger and Oetting (1976) gives a difference of 10 to 13 kcal, where K_{sp}

values are based hydrous oxides that are a few weeks old. Other researchers (Baes and Mesmer 1976) conclude a similar difference between the amorphous and crystalline oxides.

Such differences would indicate lower solubilities, by a factor of 10^7 to 10^9, for the crystalline dioxides when compared with the amorphous oxides. It is also known that, as amorphous hydroxides and hydrous oxides age, they become increasingly more crystalline, and the hydrous MO_2 very slowly approach crystalline MO_2 (Milligan and Dwight 1965; Milligan et al. 1967; Prasad, Beasley, and Milligan 1967). Despite this, there are basic reasons for using values for hydrous oxides. First, if the waste form is a material such as glass and is attacked by groundwater, it can be expected that amorphous oxide will form first as the glass matrix is dissolved, and the rate of conversion to crystalline material will be slow, particularly at low temperatures. Secondly, Rai and Ryan (1982) found that, in the case of plutonium, the crystalline oxide is made less crystalline because of the reaction of alpha particle-produced free radicals. It is this "less crystalline" material that controls measured solubilities. Although there will definitely be high radiation fields in the immediate vicinity of the waste package, this effect can be expected to become less important as distance from the package increases.

D.2 RESULTS

Thorium

Thorium has a single oxidation state, Th(IV), and therefore, will not be affected by conditions within the repository (i.e., oxidizing or reducing conditions). Since chloride complexing of Th is weak, the salinity conditions are not expected to have any appreciable effect (only relatively minor ionic strength effects). Although other compounds of Th may be less soluble, an upper limit is established by the solubility of the hydrous oxide that has been measured at PNL. Data on the effect of the carbonate ion are not available, but based on data for Np, much less effect up to 0.01 M is expected than would be predicted from tetravalent actinide carbonate complex formation constants that are available in the technical literature. On this basis, 0.01 M carbonate is not expected to produce solubilities above 5×10^{-9} M. Hydrous oxide solubilities are shown below:

pH	Th solubility, moles/liter
6	3×10^{-8}
7	6×10^{-9}
>8	$<1.5 \times 10^{-9}$

Based on measurement of the dependence of solubility on hydroxide ion concentration, the average charge for the Th species in solution from pH 6 to 10 is estimated between +1 and zero. It does not appear that the average charge is less than zero until pH exceeds 10.

The effect of increasing temperature above 25°C on the solubility of hydrous ThO_2 was not measured. It can reasonably be expected that solubility will not increase above levels found at 25°C, and it should actually very markedly decrease at least up to 200-300°C. It is well known that hydrolytic precipitation is markedly favored upon heating more acidic solutions of tetravalent actinides. It can be expected that such heating would tend to dehydrate and age the hydrous oxide to make it less hydrated and more crystalline thereby lowering its solubility, but the effect of heating on the stability of solution phase species is more difficult to predict. Conversion of hydrous ThO_2 to a fully crystalline form would probably occur below 250°C, and this effect would lower solubility by a factor of 10^8 over the values shown. Additionally, the thermodynamic concentration of the Th^{+4} ion in equilibrium with crystalline ThO_2 markedly decreases with increases in temperature. Thus, at 225°C, the thermodynamic concentration is lower by a factor of 10^8 than its value at 25°C. There is no direct data for the effect of increased temperature on hydrolysis constants, but based on the effect of temperature on fluoride complexes of Cm^{+3}, the stability of Th^{+4} hydroxy species would not be expected to increase by more than a factor of about 10^4. Since other factors were predicted to lower solubility by about a factor of 10^{16}, a decrease of a factor of 10^{10} in Th solubility over the values shown in increasing temperature from 25° to 225°C might be reasonable to expect.

Protactinium

Protactinium can be expected to be only pentavalent under environmental conditions. The chemistry of protactinium is markedly different from that of the other pentavalent actinides. It is much more like that of niobium and tantalum. There is probably no direct information on Pa solubilities, but it is markedly hydrolyzed and has extremely low solubilities even in strongly acid, noncomplexing solutions. On the other hand, it does (based on Nb and Ta chemistry) show some amphoteric behavior with greater solubility possibly occurring at higher pH values. It is estimated that Pa solubility under environmental conditions does not exceed 10^{-9} M.

Even in strong, noncomplexing acid extremely dilute solutions of Nb (and presumably also Pa) appear definitely to be highly polymeric and do not behave as typical ionic species. There is definitely no evidence of an actinyl (V) (PaO_2^+) ion as is the case of other pentavalent actinides. Solution species in the pH 6-10 region probably have charges in the low positive to low negative range.

As with Th(IV), increasing temperature at least to 200-300°C, would probably not increase the solubility of Proactinum.

Uranium

Uranium has two oxidation states (IV) and (VI), which exist under environmental conditions, and a third, U(V), which is no doubt an important solution species under reducing conditions. Under reducing conditions, UO_2 in either its crystalline or amorphous form can be expected to be the stable phase. Under oxidizing conditions, U(VI) compounds will be the stable solids and U(VI) will be the dominant form in solution.

Reducing Conditions

Under reducing conditions such as those found in basalt, UO_2 can be expected to be the stable solid phase. It is difficult to predict solubilities in terms of U(IV) in solution because hydrolysis constants reported in the literature are questionable (Baes and Mesmer 1967; Langmuir 1978; Lemire and Tremaine 1980; Phillips 1982; Allard 1982; and Barnum 1983). The published data predicts quite measurable (at least 10^{-6} $\underline{M}$ for $UO_{2(c)}$ or at least 10^{-4} $\underline{M}$ for $UO_{2(am)}$) solubility at pH 14 in terms of $U(OH)_5^-$ species. Since Ryan and Rai (1983) have shown that published data is incorrect and no evidence of amphoteric behavior with U(IV) seems to exist, all U(IV) hydrolysis constants beyond the first one are probably lower than those that have been published. If this is correct, the solubility of $UO_{2(c)}$ or $UO_{2(am)}$ as U(IV) species would be extremely low in the pH 6-10 region.

This extremely low solubility will be increased by complexing agents for U(IV) if they are present. Weak complexing agents such as Cl^- will not significantly affect this extremely low solubility. In the case of stronger complexants such as carbonate, it can also be expected that solubilities will be quite low unless carbonate levels are quite high. The carbonate complex formation constants in the literature are most certainly in error (Rai and Ryan 1984). The K_{sp} for hydrous UO_2 indicates that, at pH 10 without carbonate, the U^{+4} ion concentration will be about 10^{-36} to 10^{-37} $\underline{M}$. Assuming reasonable formation constants for carbonate complexes and bucking these against this K_{sp} would indicate that the first three carbonate complexes would not raise the solubility of U(IV) to above, at most, about 10^{-8} $\underline{M}$ even up to 1 $\underline{M}$ CO_3^{-2}. The higher carbonate complexes will probably produce appreciable solubility at such a carbonate concentration, but because the concentrations of these higher carbonate complexes in solution will follow a greater than third power carbonate dependence, these higher carbonate complexes will not be important at carbonate concentrations of environmental concern. This conclusion is in close agreement with results obtained from Np(IV) in which 0.01 $\underline{M}$ total carbonate did not raise the Np solution concentration to above the detection limit of about 5 x 10^{-9} $\underline{M}$ (Rai and Ryan 1984).

As pointed out by Krupka, Jenne, and Deutsch (1983), U(V) as the UO_2^+ ion should probably be the dominant solution species under the Eh conditions expected in a basalt repository. Using a value of pe + pH = 1.9 reported by

Jacobs and Apted (1981), a value of K_{sp} of 3×10^{-53} was derived. The following uranium solubilities, in terms of U(V), were used in deriving this K_{sp}.

pH	UO_2^+ Molarity
6	6×10^{-8}
7	6×10^{-9}
8	6×10^{-10}
9	6×10^{-11}

The value of $K_{sp} = 3 \times 10^{-53}$ was determined by plotting a straight line through values of K_{sp} for Pu(IV), Np(IV), and Th(IV) versus $1/r^2$, where r values are for the tetravalent ionic radii. This technique and the standard potential value for the reaction:

$$U^{4+} + 2\ H_2O \rightleftarrows UO_2^+ + 4\ H^+ + e^-$$

(where UO_2^+ concentrations were calculated to be pH + pe = 1.9) were used to determine the U^{+4} concentration as a function of pH. The potential value was obtained by combining values of 0.163 volts for:

$$UO_2^+ \rightleftarrows UO_2^{2+} + e^-,$$

and 0.273 volts for:

$$U^{4+} + 2\ H_2O \rightleftarrows UO_2^{2+} + 4H^+ + e^-$$

These values assume, that U(V) chemistry with regard to hydrolysis is similar to that of Np(V) but not similar to the solubility chemistry of Pa(V). They are conservative high values with regard to the value of the U(IV)-U(V) couple chosen and with regard to the fact that this is based on precipitated amorphous UO_2 rather than crystalline UO_2. Carbonate would be expected to increase the

U(V) concentrations, but at 0.01 M total carbonate, the expect total U(V) would not exceed 10^{-8} M in the pH range 6-10.

This conclusion is based on calculation of the concentrations of $UO_2CO_3^-$, $UO_2(CO_3)_2^{-3}$, and $UO_2(CO_3)_3^{-5}$ in the pH range 6-10 based on the conservative assumption that the UO_2^+ ion forms carbonate complexes of the same strength as those reported for NpO_2^+ (Maya 1983).

The calculated concentration of UO_2^{+2} at pH + pe = 1.9 in equilibrium with hydrous UO_2, and U(VI) in solution should be many orders of magnitude below U(V) in the pH 6-10 region.

Experimentally, solubility was measured as low as 10^{-8} M U at pH 7.5 in the presence of iron metal. It is probable that this represented the analytical background level.

Oxidizing Conditions

Under oxidizing conditions comparable to the presence of air, uranium is expected to be only hexavalent in both the solid and solution state. The chemistry of U(VI) under a variety of environmental conditions is complex and, as known from uranium mineralogy, a large number of difficult solid phases are possible depending on conditions. These include hydrous oxides, metal polyuranates, carbonates, complex phosphates, complex vanadates, silicates, and others. All of these probably result in much higher uranium solubilities than those under reducing conditions. Even in the absence of any complexing or precipitating anions, the behavior of U(VI) is complex. In pure water, UO_3 (or UO_2 under oxidizing conditions) solubility will be controlled by the reactions such as:

$$UO_2 + 1/2\ O_2 + H_2O \rightarrow UO_2(OH)_2 \text{ (hydrated } UO_3\text{)}$$

$$UO_2(OH)_2 \rightleftarrows UO_2OH^+ + OH^-$$

$$\text{and } UO_2(OH)_2 + H_2O \rightleftarrows UO_2(OH)_3^- + H^+.$$

Published data has not been found that demonstrates the pH attained, but this limited data would indicate that it is probably between pH 5.5 and 6. At pH 6, U solubility appears to be about 4 x 10^{-5} M. In the presence of any appreciable amounts of Na^+ or Ca^{+2}, and presumably some other metal ions, formation of solid phase polyuranates occurs. If neutral salts such as NaCl or $CaCl_2$ are the solute species, pH lowers due to reactions such as:

$$UO_2 + 1/2\ O_2 + 1/2\ H_2O + Na^+ \rightleftarrows 1/2\ Na_2U_2O_7 + H^+$$

to produce pH values in the range 4.5 to 5.0 and U solubilities (at pH 4.75) of 4 x 10^{-4} M. In the absence of metal ions precipitating polyuranates, the solubility at pH 7 is about 10^{-5} M U. Since the Na^+ and Ca^{+2} polyuranates are more stable than hydrous UO_3 above about pH 5, their solubilities should be lower. In this regard, at pH values above 5 in oxic, U solubilities under saline conditions should be lower than in nonsaline conditions.

In the presence of appreciable amounts of carbonate, U(VI) is quite soluble. Uranyl carbonate, UO_2CO_3, or Rutherfordine is known as a uranium mineral. In oxic carbonate containing environmental waters at pH values below about 10, the uranium concentration in solution in contact with UO_2 or UO_3 can be expected to approach half of the total carbonate concentration. This is based on the fact that U(VI) can be dissolved in carbonate solution up to formation of a 2/1 carbonate/uranium complex (actually apparently $[(UO_2)_3(CO_3)_6]^{-6}$ (Rai and Ryan 1984). At 0.03 M HCO_3^-, unless the system is heated, equilibrium is approached very slowly (months or more).

The effects of temperature on uranium solubility are somewhat difficult to predict. Under reducing conditions, factors include change of crystallinity of the hydrous oxide, the effect of temperature on the equilibrium solubility as the M^{+4} ion, the effect of temperature on U^{+4} - UO_2^+ equilibrium, the effect of temperature on hydrolysis constants for U^{+4}, and the effect of temperature on carbonate complexation of MO_2^+. These calculations for the solubility of MO_2 type materials has been conservative because of the use of values for the more soluble hydrous oxides. If the temperature was raised 200° (to 225°C), the crystalline oxide would be expected to form rather rapidly with a lowering in solubility (over the estimate) of possibly a factor of 10^8. In addition, the equilibrium constant for the reaction:

$$UO_2 + 4H^+ \rightleftarrows U^{+4} + 2\ H_2O$$

decreases in going from 25°C to 225°C by a factor 2.5×10^6 based on entropy values and heats of formation values for UO_2 and U^{+4} from (Fuger 1972) and (Fuger and Oetting, 1976) and for H_2O from (Latimer 1952). Again, as in the Th case, the effect of temperature on the U^{+4} hydrolysis constants is hard to predict, but, in any case, the soluble M(IV) hydrolytic species would not be expected to increase in stability adequately to exceed the M(V) concentration as the principal solution species. For the oxidation of U^{+4} to UO_2^+, a particular oxidant must be assumed before the effect of temperature can be calculated. Assuming the H_2S-S couple (the potential of this couple is very near pH + pe = 1.9), the overall reaction is:

$$U^{+4} + 1/2\ S + 2\ H_2O \rightleftarrows UO_2^+ + 1/2\ H_2S + 3H^+.$$

Using U^{+4} and UO_2^+ heat of formation and entropy data from (Fuger and Oetting, 1976) and for S, H_2O, and H_2S from (Latimer 1952), the equilibrium is shifted to the right by (solubility is increased by) a factor of 5×10^7 in going from 25° to 225°C. If the somewhat weaker oxidant, H_2O had been assumed, instead of sulfur, this increase would have been a factor 10^9. In addition to this, some increase (perhaps a factor of 10 to 100) would be expected in the stability of U(V) carbonate complexes (based on extrapolation from data for oxalate complexes (Jones and Choppin 1969) on increasing temperature by 200°. Overall, these effects will probably not compensate for the conservative use of hydrous rather than crystalline UO_2 solubility, but they may be coming close and further increasing temperature (above 225°C) might increase solubilities above 10^{-8} <u>M</u> at pH + pe = 1.9.

The effect of temperature on the solubility of U under oxic conditions, where solubility is already high at 25°C, is difficult to estimate because so little is known about the various possible solid phases as well as about the solution species. Overall, considering the nature of these species, my best educated guess would be that overall solubilities would be more likely to rise than to decrease.

Neptunium

Neptunium can be expected to have two oxidation states under environmental conditions, Np(IV) and Np(V). A third oxidation state, Np(VI), might be possible under strong complexing oxic conditions but does not appear too likely. Under reducing conditions, NpO_2 is almost certainly the stable solid phase. The solid phase is somewhat less certain under oxidizing conditions. Strickert, Rai, and Fulton (1984) have reported some evidence of a Np(V) solid phase forming in oxic solutions above pH 8.5.

Reducing Conditions

Under reducing conditions such as those found in basalt, Np can be expected to be very insoluble over the entire environmental pH range. The equilibrium amount of Np(V) in the presence of hydrous NpO_2 under reducing, pe + pH = 1.9, conditions can be calculated to decrease from about 10^{-13} $\underline{M}$ at pH 6 to about 10^{-17} $\underline{M}$ at pH 10. The calculation is based on a log K_{sp} of -53.5 for hydrous NpO_2 and $E° = 0.670$ volts for the Np(IV)-Np(V) couple (Fuger and Oetting 1976). This means that Np is undoubtedly less soluble than U under reducing conditions and makes it quite possible that Np(IV) hydroxy species may dominate in solution. Since no evidence was found of amphoteric behavior for Np(IV) down to about 5×10^{-9} $\underline{M}$ Np at 1 $\underline{M}$ OH^- indicating that all, except possibly the first, hydrolysis constants are no doubt lower than indicated in the literature, Np(IV) solubilities in the pH range 6-10 are probably many orders of magnitude lower than the limit of 5×10^{-9} $\underline{M}$ measured in this range.

If one assumes the same continuous progression which has been proposed by various others (Baes and Mesmer 1976, Langmuir 1978, Lemire and Tremaine 1980, Phillips 1982, Allard 1982, and Barnum 1983) for log hydrolysis constant values for $M(OH)_x^{m-x}$, the lower hydrolysis constants are limited by a recently measured limit for log $\beta_5 < -24.7$ for Np(IV) (Rai and Ryan 1984). Calculation of such limits (particularly for β_3 and β_4) would indicate that total Np(IV) solubility as Np(IV) hydroxy species would not exceed about 10^{-12} M in the pH 6-10 region.

Saline conditions are not expected to appreciably affect these low solubilities. Carbonate complexing, as in the discussion on U(IV), is not expected to produce appreciable Np(IV) solubility except at high carbonate levels. At 0.01 M total carbonate, Np(IV) is still found at or below the detection limit of 5×10^{-9} M at all pH values in which CO_3^{-2} or HCO_3^- are stable. The real value is no doubt much lower.

As in the case of U under reducing conditions, and for the same reasons, we do not expect increase in temperature from 25°C to 225°C to raise the solubility to above the 10^{-12} M value in the pH 6-10 range stated above.

Oxidizing Conditions

Under oxidizing conditions, NpO_2 is still probably the stable solid phase at least below pH 8.5, but Np is relatively quite soluble as Np(V) in solution. If a Np(V) solid phase does form above pH 8.5 but not below that pH level (Strickert, Rai, and Fulton 1984), its solubility would be equal to that of NpO_2 at pH 8.5 and could not vary greatly from it in the narrow pH range 8.5 to 10. At pH + pe = 13.6, hydrous NpO_2 solubility as Np(V) should decrease from about 6×10^{-3} M at pH 6 using initially crystalline NpO_2, which should be less soluble. However, the solubility appeared to very slowly increase with time, and it may be that some less crystalline NpO_2 slowly formed due to radiolytic reactions, which occur at a faster rate for PuO_2.

Strickert, Rai, and Fulton (1984) have also studied hydrous NpO_2 solubility and obtained values of about 10^{-3}-10^{-4} M at pH 6 with fresh hydrous NpO_2. In this case, solubility decreases with time and the characteristic X-ray pattern of NpO_2 can be obtained as the material progresses toward more crystalline oxide.

The effect of saline conditions is probably minimal on Np under oxidizing conditions. Carbonate will probably increase solubility. At a free carbonate ion concentration of 0.01 M, solubilities of about a factor of 10^3 higher than those quoted above might be expected based on literature values of Np(V) carbonate formation constants which appear reasonable. It must be noted in regard to this statement that as pH decreases below about 10, the free carbonate to total carbonate ratio drops rapidly so that this magnitude of effect will not occur at lower pH values.

As in the case of U under oxidizing conditions, it is difficult to predict the effect of temperature under oxidizing conditions, but solubility is not necessarily expected to decrease appreciably and solubilities in the range 10^{-5} M to 10^{-3} M are not unreasonable.

Plutonium

Although Pu(IV) is no doubt the most stable solid phase oxidation state of Pu under oxidizing conditions, it is possible, particularly at low pH, but certainly unproven, that under highly reducing conditions a Pu(III) solid phase might form. In solution, under oxidizing conditions, Pu(V) and possibly Pu(VI) are expected under environmental pH conditions, and under reducing conditions Pu(III) and Pu(IV) are expected.

Reducing Conditions

Under reducing conditions, plutonium chemistry will be that of the tetravalent and trivalent state. As noted for Th through Np in the tetravalent state, the hydroxy complexes are much weaker than the literature indicates. Although no direct data on Pu was found, it is known that Np(IV) does not show amphoteric species down to 5×10^{-9} M at pH 14. The adjacent actinide Pu(IV) would not be more than at most two orders of magnitude more soluble, if any more at all, at pH 14. Since the solubilities are definitely expected to be considerably lower in the pH 6-10 region than any caused by an amphoteric species at pH 14, soluble Pu(IV) would be below 5×10^{-9} M over the pH 6-10 region in equilibrium with hydrous PuO_2. Complexing with carbonate up to 0.01 M free CO_3^{-2} should not cause Pu(IV) concentrations above that value. The solubility product of the tetravalent hydrous oxide decreases with atomic number and decreasing ionic radius. Although hydrolysis constants and carbonate complex formation constants are expected to increase in the same direction with atomic number they would certainly not be expected to more than compensate for the decreasing K_{sp}.

In a system free of other precipitates and at a pH + pe of 1.9 (basalt water), Pu(III) should be the dominant solution species. Based on Rai's value of K_{sp} for $PuO_{2(am)}$, Fuger and Oetting's (1976) value for the Pu(III)-(IV) potential, and assuming that Pu(III) has the same hydrolysis constants Rai et al. (1983) found for the adjacent trivalent actinide, Am(III), the following Pu(III) concentrations were found to exist with $PuO_{2(am)}$ at pH + pe = 1.9:

pH	Pu(III) Total (M)
5	0.14
6	1.4×10^{-4}
7	1.4×10^{-7}
8	$<2.5 \times 10^{-10}$
9	$<2.5 \times 10^{-12}$
10	1×10^{-13}

The above values show rather high Pu concentrations as Pu(III) at pH 7 and below. It should be noted, however, that Rai et al. (1981) found that the adjacent trivalent actinide, Am(III), appears to be solubility rather than adsorption controlled in the presence of various soils and minerals. The solubilities observed were below 10^{-9} M at pH 5 and decreased with the first power of the OH^- concentration. This solid phase was not identified, but it should also be noted that the chemically virtually identical light rare earths are extremely insoluble in nature and insoluble minerals include the simple phosphates and fluorocarbonates. Under such reducing conditions then, a Pu(III) solid rather than PuO_2 may be solubility controlling.

As in the case of the other tetravalent actinides, carbonate at typical ground and rock water levels will produce solubilities up to the detection limit for Pu(IV); certainly not above 5×10^{-9} M. Carbonate may, however, increase Pu solubility as Pu(III). This is not expected to greatly increase solubilities over those shown above because of the low solubilities of the Pu(III) basic carbonates and fluorocarbonates themselves. There is no apparent evidence of solubilization of light lanthanides in nature by this route.

Increasing temperature would be expected to appreciably lower the solubility of Pu relative to the values shown above under reducing conditions. Again, as in the cases of Th, U, and Np, increasing temperature will convert the oxide to a more crystalline form of lower solubility and will lower the solubility of crystalline PuO_2 itself to produce Pu^{+4} in solution. This effect should more than compensate for any increase in Pu(IV) hydrolysis constants. Since Pu(III) is expected to be the dominant solution species though under reducing conditions, the effect of temperature on the reductive dissolution will probably be controlling. Again, assuming the redox potential to be controlled by the H_2S-S couple, the following reaction occurs:

$$PuO_2 + 3H^+ + 1/2\ H_2S \rightleftarrows Pu^{3+} + 1/2\ S + 2\ H_2O.$$

Using Pu thermodynamic data of Fuger and Oetting (1976), and data from Latimer (1952), it can be concluded that the equilibrium constant for the above reaction decreases by a factor of 10^6 when temperature increases from 25°C to 225°C. Thus, overall, a lowering of solubility of PuO_2 is expected on increasing temperature in a reducing repository.

Oxidizing Conditions

Rai, Serne, and Moore (1980), Rai and Swanson (1981), and Wedepohl (1969 and 1970) have shown that the solubility of PuO_2 under oxidizing (air) conditions involves the following reaction:

$$PuO_2 + 1/4\ O_2 + 1/2\ H_2O \rightarrow PuO_2^+ + OH^-.$$

The measured solubilities of PuO_2 as a function of pH are as shown below:

pH	PuO_2-239$_{(c)}$(a)	PuO_2-239$_{(am)}$(a)
5	6×10^{-8} M	6×10^{-6} M
6	1.6×10^{-8}	1×10^{-6}
7	3×10^{-9}	2×10^{-7}
8	6×10^{-10}	3×10^{-8}

(a) The PuO_2-239$_{(am)}$ gradually becomes less soluble and shows greater but far from complete crystallinity on long (a few years) aging, and the measured $PuO_{2(c)}$ solubility is controlled by the presence of some "less crystalline" material which rapidly forms through radiolytic reactions with water (Rai and Ryan, 1982). The two materials approach an identical, very poorly crystalline state in a few (~3-5) years.

As in the case of Np, carbonate would be expected to increase the solubility of PuO_2 in an oxidizing environment by perhaps one thousand-fold at pH 10 and 0.01 M CO_3^{-2}. It is also possible that carbonate complexing might stabilize the Pu(VI) state. Less effect will occur at lower pH values at the same total carbonate concentrations and considerably less effect will occur at lower carbonate levels. A large effect of saline versus nonsaline is not expected except for ionic strength effects and the effect on the pe value due to radiolysis of the NaCl solution. This makes the solution more oxidizing resulting in appreciable solubility increase, but this will be only a near-field effect where there is appreciable radiation intensity.

For the reaction:

$$PuO_2 + 1/4\ O_2 + H^+ \rightleftarrows PuO_2^+ + 1/2\ H_2O$$

the equilibrium constant, and thus presumably the solubility as PuO_2^+, decreases by only a factor of 1.3 in the temperature range from 25°C to 225°C. The value of the equilibrium constant at 25°C would predict a solubility of fully crystalline PuO_2 in full thermodynamic equilibrium with air of about 8×10^{-15} M

PuO_2^+ at pH 8. The measured value for hydrous PuO_2 at pH 8 is about 3×10^{-8} M or a factor of about 4×10^6 higher than predicted for the crystalline material. Since, as noted earlier, we predicted 10^7 to 10^9-fold lower solubility for crystalline than for hydrous oxide, this value would indicate that oxygen is oxidizing to approximately its full thermodynamic potential, and the difference is fully ascribable to difference in oxide crystallinity. Because of this, the effect of increased temperature is expected to be only that affecting the PuO_2 crystallinity. Even with the radiolytic decrease in crystallinity observed by Rai and Ryan (1982), some net increase in steady-state PuO_2 crystallinity with increase in temperature, and thus some decrease in solubility in an oxygen environment, could be expected. This decrease would be no more than six orders of magnitude as an absolute limit, and it would probably be less.

Americium

Americium can be expected to be only trivalent under environmental conditions and is thus expected not to behave differently under oxidizing or reducing conditions. The solubility of $Am(OH)_3$ is quite low, $<10^{-10}$ M, at or above pH 10.5 but increases rapidly at lower pH values (Rai et al. 1983).

pH	Am, M
10	3×10^{-10}
9	3×10^{-9}
8	3×10^{-7}
7	3×10^{-4}

Because of these high solubilities at low pH values (<8), it is highly unlikely that $Am(OH)_3$ would control solubility in this range and perhaps would not at higher pH values. Am, like the lanthanides, forms insoluble phosphates, fluorides, basic carbonates, carbonate-fluorides, complex silicates, complex oxides (particularly with pentavalent metals and others). Rai, et al. (1981) have found the solubility of Am in contact with soils and a variety of minerals to be controlled by an unidentified solid having much lower solubilities than that of $Am(OH)_3$. These values decreased with approximately the inverse first power of the pH. The values probably represent much more realistic values for upper limits of solubility of Am in the environment.

pH	Am, M
5	6×10^{-10}
6	6×10^{-11}
7	6×10^{-12}
8	6×10^{-13}

An effect of saline versus nonsaline is not expected to be any greater than an ionic strength effect. The effect of carbonate up to 0.01 M would probably not be to bring any concentrations above 10^{-10} M. By comparison, the soluble portion of total trivalent lanthanides is less than 10^{-10} M in seawater having pH 8.15 and 0.0025 M total carbonate (Wedepohl 1969, 1970).

Curium

Curium will be only trivalent under environmental conditions, and as an adjacent actinide of Am, its chemistry in the environment can be expected to closely follow that of americium.

D.3 APPENDIX D REFERENCES

Aberg, M., et al. 1983. Inorg. Chem. 22:3981.

Allard, B. 1982. In "Actinides in Perspective". (N. Edelstein, ed.) Peragamon Press, New York, pp. 553-580.

Baes, C. F., Jr. and R. E. Mesmer. 1976. The Hydrolysis of Cations, Wiley, New York.

Barnum, D. W. 1983. Inorg. Chem. 22:2297.

Fuger, J. 1972. MTP Int. Rev. Sci. K. W. Bagnall, ed., Series One, Vol. 7, p. 157.

Fuger, J. and F. L. Oetting. 1966. "The Chemical Thermodynamics of Actinide Elements and Compounds - II. The Actinide Aqueous Ions." Intl. Atomic Energy Agency, Vienna, Austria.

Jacobs, G. K. and M. J. Apted. 1981. "Eh-pH Conditions for Groundwater at the Hanford Site, Washington: Implications for Radionuclide Solubility in a Nuclear Waste Repository Located in Basalt." EOS (Amer. Geophysical Union), 62:1065 (Abstract).

Jones, A. J. and G. R. Choppin. 1969. Actinides Rev. 1:311.

Krupka, K. M., E. A. Jenne, and W. J. Deutsch. 1983. "Validation of the WATEQ4 Geochemical Model for Uranium," PNL-4333, Pacific Northwest Laboratory, Richland, Washington.

Langmuir, D. 1978. Geochim. et Cosmochim. Acta. 30:213.

Latimer, W. M. 1952. "Oxidation Potentials," 2nd ed., Prentice-Hall, Englewood Cliffs, New Jersey.

Lemire, R. J. and P. R. Tremaine. 1980. J. Chem. Eng. 25:361.

Maya, L. 1983. Inorg. Chem. 22:2093.

Milligan, W. O. and D. W. Dwight. 1965. J. Electron Microscopy, 14:264.

Milligan, W. O., et al. 1967. Acta Cryst, B24:979.

Oetting, F. L., M. H. Rand, R. J. Ackerman. 1976. "The Chemical Thermodynamics of Actinide Elements and Compounds - I. The Actinide Metals." Intl. Atomic Energy Agency, Vienna, Austria.

Phillips, S. L. 1982. "Hydrolysis and Formation Constants at 25°C," LBL-14313.

Prasad, R., M. L. Beasley, and W. O. Milligan. 1967. J. Electron Microscopy, 16:101.

Rai, D. and J. L. Ryan. 1982. Radiochim. Acta. 30:213.

Rai, D., and J. L. Ryan. 1984. PNL-SA-12096, Pacific Northwest Laboratory, Richland, Washington. Submitted to Inorg. Chem.

Rai, D., R. G. Strickert, and G. L. McVay. 1982. Nucl. Tech. 58:59.

Rai, D., et al. 1983. Radiochim. Acta. 33:201.

Rai, D., et al. 1981. Geochim. Cosmochim. Acta. 45:2257.

Rai, D., R. J. Serne, and D. A. Moore. 1980. Soil Science Soc. Am. J. 44:490.

Rai, D., R. J. Serne, and J. L. Swanson. 1980. J. Environ. Qual. 9:417.

Rai, D. and J. L. Swanson. 1981. Nucl. Tech. 54:107.

Ryan, J. L. and D. Rai. 1983. Polyhedron, 2:947.

Strickert, R. G., D. Rai, and R. W. Fulton. 1984. ACS Symp. Series. 246:135.

Wedepohl, K. M., ed. 1969 and 1970. "Handbook of Geochemistry," Vol. II/1, Springer-Verlag, New York.

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