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May 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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EVALUATION OF ALTERNATIVE TREATMENTS FOR SPENT FUEL ROD CONSOLIDATION WASTES AND OTHER MISCELLANEOUS COMMERCIAL TRANSURANIC WASTES

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ABSTRACT

Eight alternative treatments (and four subalternatives) are considered for both existing commercial transuranic wastes and future wastes from spent fuel consolidation. Waste treatment is assumed to occur at a hypothetical central treatment facility (a Monitored Retrieval Storage facility was used as a reference). Disposal in a geologic repository is also assumed. The cost, process characteristics, and waste form characteristics are evaluated for each waste treatment alternative. The evaluation indicates that selection of a high-volume-reduction alternative can save almost $1 billion in life-cycle costs for the management of transuranic and high-activity wastes from 70,000 MTU of spent fuel compared to the reference MRS process. The supercompaction, arc pyrolysis and melting, and maximum volume reduction alternatives are recommended for further consideration; the latter two are recommended for further testing and demonstration.

SUMMARY

This evaluation compares eight major alternatives and four subalternatives for the treatment of commercial transuranic waste (TRUW) and high-activity waste (HAW) based on their product characteristics, process characteristics, and total system economics. The study recommends further consideration of the supercompaction, arc pyrolysis and melting, and maximum volume reduction (MVR) alternatives and also recommends testing and demonstration of the last two alternatives. This study was prepared for the U.S. Department of Energy (DOE) as part of the Nuclear Waste Treatment Program (NWTP) being conducted by the Pacific Northwest Laboratory (PNL).[a]

The wastes selected for consideration in the study include all commercial TRUW that have been generated and are expected to be generated in the foreseeable future. The major wastes may originate from a central treatment facility for spent fuel rod consolidation, either a Monitored Retrievable Storage (MRS) facility (if approved by Congress) or a similar facility at a future selected repository.[b] The conceptual MRS facility design was used as the reference to define waste-generation information. An estimated 1,300 m^3/yr of untreated wastes are to be generated from spent fuel rod consolidation activities. All other TRUW from non-spent fuel rod consolidation activities at other commercial sites can be processed at a rate of 500 m^3/yr. The MRS facility wastes are mostly the spent fuel hardware and contaminated high-efficiency particulate air (HEPA) filters from the central treatment facility. Cemented wastes are expected to be the largest volume of non-MRS civilian wastes. The HEPA filters are a challenging treatment problem because they contain organic, metallic, and ceramic materials in intimate combination. Additional types of waste include failed equipment, ion-exchange resins, solutions and sludges, mixed combustibles, and filters.

(a) Pacific Northwest Laboratory is operated for the Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

(b) The MRS facility and geologic repository as addressed in this report are understood to be facilities currently being evaluated by the DOE as potential nuclear waste treatment and long-term waste storage and disposal facilities.

Table S.1 summarizes the treatment alternatives that were analyzed. Each alternative provides a treatment method for each of the various wastes. Most of the alternatives would produce several different waste forms and use a number of processes. These alternatives provide a wide spectrum of choices both in process complexity and in waste form quality. Most of the alternatives were not optimized before their selection and evaluation, and therefore serve only as general guidance for the decision-making process. However, Maximum Volume Reduction (MVR) subalternatives (4A, 4B, 4C, and 4D) were subsequently evaluated to optimize Alternative 4 and provide better direction to future technology demonstration activities related to this alternative.

Although the disposal method for these wastes has not been selected, it has generally been assumed that the wastes would go to a combined defense/commercial repository. This assumption was used in this study to evaluate costs and potential requirements. If a nongeologic disposal method is selected, analysis and results could differ from those described in this report. Because the waste form characteristics required for disposal have not been established, no minimum requirements were used to eliminate any treatment alternative. The major concerns about waste form quality relate to the following potential requirements:

- low release rate to meet the U.S. Nuclear Regulatory Commission (NRC) limit of less than 1 part in 100,000/yr released from engineered barriers
- no organics or combustible materials
- immobilized particulates
- no pyrophoric potential
- structural stability (<20% void volume in packages)
- radiation resistance.

Using a numerical ranking method and the above potential requirements we arrived at the ranked product values shown in Table S.2, where the lowest numerical value corresponds to the best.

TABLE S.1. Summary of Selected Treatment Alternatives for all Commercial TRUW and HAW

Alternative	General Treatment Scheme
1. No Treatment	Package without treatment
2. MRS Reference	Shred NFBC,[a] compact HEPA filters, cement miscellaneous wastes
3. Supercompaction	Compact using high pressure for high volume reduction without high temperatures
4. MVR with Decontamination	Melt activated metals, decontaminate non-activated metals, incinerate combustibles and organics, and melt cements, residues, and oxides
4A. MVR with Decontamination and Melting	Treat all wastes the same as 4 except: no treatment of cemented wastes from other facilities; and combined remote-handled treatment of combustibles, ashes, filter media, and residues
4B. MVR with Melting Only	Treat all wastes the same as in 4A except melt rather than decontaminate metal wastes
4C. MVR with Decontamination and Cementing	Treat all wastes the same as in 4A except oxides and residues from incineration and decontamination are cemented
4D. MVR with Cementing Only	Treat all wastes the same as in 4C except melt rather than decontaminate metals
5. Cementation	Encapsulate all wastes in cement grouts or castings
6. Arc Pyrolysis and Melting	Treat all wastes in an arc pyrolysis melter, which will pyrolyze all organics and combustibles, and melt all other materials
7. Sulfur-Bonded Graphite	Melt all metals, incinerate combustibles, and combine ash and residues into a sulfur-bonded graphite
8. Highest-Quality Waste Form	Incinerate organics and combustibles, melt all metals, hot-press residues, ashes, and ceramics

(a) NFBC = non-fuel-bearing components of spent fuel.

TABLE S.2. Values of the Waste Treatment Alternatives by Waste Form Characteristics and Process Characteristics[a]

	Alternatives	Waste Form Value	Process Value
1.	No Treatment	1,700	690
2.	MRS Reference	1,100	1,700
3.	Supercompaction	940	2,400
4.	MVR with Decontamination	430	16,000
4A.	MVR with Decontamination and Melting	610	9,300
4B.	MVR with Melting Only	600	8,500
4C.	MVR with Decontamination and Cementing	660	8,300
4D.	MVR with Cementing Only	650	7,500
5.	Cementation	1,200	3,600
6.	Arc Pyrolysis and Melting	580	7,700
7.	Sulfur-Bonded Graphite	620	14,000
8.	Highest-Quality Waste Form	230	20,000

(a) Lowest values are best.

The processes in each of the alternatives were also numerically ranked by combining the value for each process for both the contact-handled (CH) and the remote-handled (RH) wastes based on their processing characteristics of operational safety, processing simplicity, and status of technology. Table S.2 shows the combined CH and RH product and process values and indicates the desirability of the single-process or few-process alternatives. Here, too, the lowest numerical value is the best.

Based on waste composition and expected product characteristics, the volumes of treated waste were calculated for each of the alternatives. These volumes can significantly impact the costs of transportation and repository disposal (Table S.3). The treatment costs include the costs of the equipment, facility, certification, canisters, emplacement of waste in canisters, four-month interim storage capability for the treated wastes, and decommissioning. The transportation costs are based on shipping the wastes 2,000 miles by train.

TABLE S.3. Final Waste Volumes and Total Life-Cycle Costs for Management of TRUW and HAW from 70,000 MTU[a]

	Alternatives	Final Waste Volume, m^3	Treatment Costs: Capital, Operating, & Decommissioning, $M	Transportation Costs: Capital & Operating, $M	Disposal Costs, $M	Totals, $M	Savings Compared to MRS Reference, $M
1.	No Treatment	2,900	210	971	2,055	3,236	(1,460)[b]
2.	MRS Reference	1,090	123	326	1,327	1,776	--
3.	Supercompaction	385	84	116	743	943	833
4.	MVR with Decontamination	181	172	84	531	787	989
4A.	MVR with Decontamination and Melting	267	128	113	622	863	913
4B.	MVR with Melting Only	294	121	104	631	856	920
4C.	MVR with Decontamination and Cementing	338	123	129	731	983	793
4D.	MVR with Cementing Only	378	113	119	736	968	808
5.	Cementation	1,345	145	387	1,437	1,969	(193)[b]
6.	Arc Pyrolysis and Melting	212	151	89	562	802	947
7.	Sulfur-Bonded Graphite	400	142	122	732	996	780
8.	Highest-Quality Waste Form	250	210	108	619	937	839

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) Added cost compared to Alternative 2.

The disposal costs are based on disposal of the wastes in a postulated basalt repository with the spent fuel. All costs are based on 70,000 MTU of spent fuel.

The disposal cost dominates the total system cost, followed by transportation costs, and then treatment costs. Savings in transportation costs alone justify more extensive treatment of the wastes to reduce the volume. Treatment costs account for only 7% to 22% of the total system cost, depending on the alternatives considered. Furthermore, there are additional large potential savings when comparing the more extensive treatment alternatives to the MRS facility alternative. These savings appear to justify a significant effort to develop, demonstrate, and implement volume reduction technology for these wastes.

To obtain a single value for each process, we first normalized the waste form and process values in Table S.2 and the costs shown in Table S.3, and then the normalized values were summed. To normalize a given set of values, the lowest value was divided into the other values such that the lowest value was one. The scale was then expanded linearly so that the largest value was 100. These ratings are shown in Table S.4. This normalization procedure puts costs, waste form characteristics, and process characteristics on similar numerical scales, which can then be added directly or can be multiplied by weighting factors and then added. Based on this evaluation, supercompaction, MVR, and arc pyrolysis and melting are the best alternatives. In addition to the direct summation of the ratings for costs and characteristics shown in the last column of Table S.4, weighting factors of between one and nine were also applied. At least one of the top three alternatives identified by equal weighting was also a top alternative when other weightings were applied.

Supercompaction is a developed technology and is commercially available. However, the products from supercompaction would not meet many of the potential disposal requirements noted previously. The arc pyrolysis and melting process is untested but has been designed for treatment of capacitors containing polychlorinated biphenyls (PCBs) and for treatment of municipal garbage. It is an attractive process but considerable testing and demonstration would be required for TRUW treatment needs. The MVR alternative had the lowest

TABLE S.4. Summary of Waste Form, Process, and Economic Ratings for Each Alternative[a]

	Alternative	Waste Form Rating	Process Rating	Economic Rating	Total
1.	No Treatment	100	1	100	201
2.	MRS Reference	61	7	36	104
3.	Supercompaction	48	10	7	65
4.	MVR with Decontamination	15	79	1	95
4A.	MVR with Decontamination and Melting	29	45	4	78
4B.	MVR with Melting Only	28	41	5	74
4C.	MVR with Decontamination and Cementing	33	40	7	80
4D.	MVR with Cementing Only	33	36	9	77
5.	Cementation	64	16	45	125
6	Arc Pyrolysis and Melting	24	37	2	63
7.	Sulfur-Bonded Graphite	27	70	10	107
8.	Highest-Quality Waste Form	1	100	6	107

(a) Lowest values are best.

potential cost but requires numerous processes, many of which have been previously used for nuclear waste treatment.

The evaluation of MVR subalternatives (4A, 4B, 4C, and 4D) indicates that an optimized strategy would not treat the previously cemented wastes, nor would it decontaminate the nonactivated metals. Both of these process simplifications would come at the expense of higher total costs.

It is recommended that after additional demonstration of the arc pyrolysis and melting process and the MVR process, an additional evaluation and comparison of the two processes should be conducted before a final decision is made on which treatment technology to implement.

CONTENTS

FIGURES

TABLES

GLOSSARY

BNFP	Barnwell Nuclear Fuel Plant
BWIP	Basalt Waste Isolation Project
BWR	boiling water reactor
CFR	Code of Federal Regulations
CH	contact-handled
CH-TRUW	contact-handled transuranic waste(s)
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
HAW	high-activity waste(s)
HEPA	high-efficiency particulate air
HLW	high-level waste
INEL	Idaho National Engineering Laboratory
LLW	low-level waste(s)
MRS	Monitored Retrievable Storage
MTU	metric tons of uranium
MVR	maximum volume reduction
NWTP	Nuclear Waste Treatment Program, PNL, Richland, WA
NFBC	non-fuel-bearing components
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
OCRWM	Office of Civilian Radioactive Waste Management
PCBs	polychlorinated biphenyls
PNL	Pacific Northwest Laboratory, Richland, WA
PVC	polyvinyl chloride
PWR	pressurized water reactor
R&D	research and development
RECON	Repository Economics
RH	remote-handled
RH-TRUW	remote-handled transuranic waste(s)
TRU	transuranic

TRUPACT	Transuranic Package Transporter
TRUW	transuranic waste(s)
WAC	Waste Acceptance Criteria
WAPS	Waste Acceptance Preliminary Specifications
WIPP	Waste Isolation Pilot Plant

1.0 INTRODUCTION

The study documented in this report was performed for the Department of Energy (DOE) as part of the Nuclear Waste Treatment Program (NWTP) being conducted by Pacific Northwest Laboratory (PNL). The study was conducted in collaboration with related work being carried out for the DOE Office of Civilian Radioactive Waste Management (OCRWM). The objective of this study is to provide analyses of various transuranic waste (TRUW) treatment alternatives at an MRS facility (or a repository receiving and handling facility) and the cost impacts of these alternatives on the total waste management system.

Transuranic waste and high-activity waste (HAW) may be generated during the spent fuel handling and consolidation operations for commercial spent fuel at either a Monitored Retrievable Storage (MRS) facility (U.S. DOE 1986a), if approved by Congress, or at a receiving and handling facility at a deep geologic repository. These categories of waste may also be generated in smaller amounts by various research laboratories, nuclear power reactors, the decommissioning of mixed oxide fuel fabrication plants, and other commercial facilities using transuranic (TRU) radionuclides.

Transuranic waste is defined as material contaminated with TRU radionuclides in concentrations greater than 100 nCi/g of waste. Transuranic waste can be present in a wide variety of forms. Original commercial TRUW forms are expected to include failed equipment, fuel hardware resulting from spent fuel consolidation, ventilation filters, process cartridge filters, process solutions and sludges, spent ion exchange media, previously cemented wastes, concrete rubble from the decommissioning of nuclear facilities, and general trash (which can include paper, rags, wood, glass, metals, plastics, and ceramics). The final disposition of commercial TRUW has not been determined, but it is expected to be in deep geologic repositories similar to the disposition of commercial spent nuclear fuel and high-level waste (HLW). In this case, the TRUW, in combination with other engineered barriers in the repository, may be required to meet the U.S. Nuclear Regulatory Commission's (NRC's) requirement for limiting the fractional release rate of radionuclides to less than 1 part in 100,000/yr. It is likely that most of the wastes will need some type of treatment to meet this limit. Tests of the selected final waste forms will be needed to confirm their acceptability.

High-activity wastes are generated in reactors where structural materials in the fuel assemblies are subjected to high neutron fluxes and become radioactive. Steels containing cobalt become activated to the greatest extent due to the formation of cobalt-60. Niobium-94 and nickel-59 are also formed in sufficient concentrations to be of concern. The concentrations of these three isotopes are often sufficiently high that the wastes exceed the limits for Class C LLW as defined in 10 CFR 61 and therefore are excluded from low-level waste (LLW) disposal. In a previous study (Ross et al. 1985), it was noted that the disposal of HAW at an LLW site may also be more expensive than disposal of HAW in a geologic repository. Therefore, HAW is being considered along with the TRUW in this study. Disposal requirements have not yet been established for these wastes.

The MRS facility (if implemented) or the repository receiving and handling facility will generate the largest amount of TRUW from civilian nuclear activities. The MRS facility is to be a central facility for fuel rod consolidation and emplacement of waste in canisters and for interim storage of commercial spent nuclear fuel and HLW. Because this large facility must have systems for treatment of its internally generated TRUW (and LLW), it is reasonable to consider it as a potential central treatment facility for the treatment of the smaller amounts of TRUW generated in the myriad of commercial facilities prior to their disposal. It may well be impractical for the other TRUW-generating facilities, which are typically small, to convert their TRUW into a form suitable for disposal. If the MRS facility is not implemented, the geologic repository will have equivalent facilities for consolidating and packaging the incoming spent fuel and HLW (U.S. DOE 1985a); and the repository may generate amounts of TRUW similar in nature to those expected to be generated by the MRS facility. In this case, the repository could serve as a central facility for receiving, treating, and packaging TRUW from the other civilian sources.

The MRS facility (or the repository receiving and handling facility) and the other generators of TRUW from civilian nuclear activities will generate a broad range of TRUW forms. These wastes will also have a broad range of beta-gamma radioactivity levels which will require shielding and remote handling of significant amounts of the TRUW. The MRS facility (or the repository receiving and handling facility) will generate TRUW that includes almost all of the waste forms and radioactivity characteristics expected from the other TRUW sources. Because of the wide variety of original TRUW forms, it is reasonable to consider and evaluate the impact of alternative treatments on the waste management system and the impact of using the MRS facility (or the repository receiving and handling facility) for treating TRUW from the other sources.

Eight alternatives (with differing fundamental objectives) and four sub-alternatives have been analyzed and are described in this report. The results of the study provide the DOE with a basis for making decisions and further evaluations about the scope, schedule, and budget for TRUW studies. This study also provides input to the DOE for waste treatment alternatives at the MRS facility or deep geologic repository.

2.0 CONCLUSIONS AND RECOMMENDATIONS

This study on treatment alternatives for commercial HAW and TRUW has identified the directions and incentives for treatment of these wastes. Three types of conclusions and recommendations are made: first, general observations on important factors identified in the evaluation; second, recommendations on the preferred alternatives of those evaluated; and third, recommendations for further work.

2.1 GENERAL OBSERVATIONS AND CONCLUSIONS

- The disposal method and waste form requirements for disposal of TRUW are uncertain and need to be defined. The lack of definitive requirements for the waste forms may result in the design and implementation of more costly or inadequate treatment technologies. Disposal of TRUW in a deep geologic repository with requirements similar to HLW will require that the wastes be extensively treated. The major concerns about waste form quality relate to the following potential requirements:
  - low release rate to meet the NRC limit of less than 1 part in 100,000/yr released from engineered barriers
  - no organics or combustible materials
  - immobilized particulates
  - no pyrophoric potential
  - structural stability (<20% void volume in packages)
  - radiation resistance.
- There are major opportunities to reduce the volume and increase the quality of the waste forms for TRUW and HAW.
- Processes that can treat all of the wastes in a single system, such as supercompaction and arc pyrolysis and melting, are very attractive from a processing perspective.

- Volume reduction strongly influences the transportation and disposal costs and can significantly improve disposal economics.
- Extensive treatment could result in life-cycle system savings of nearly $1 billion for 70,000 MTU of spent fuel.
- High-efficiency particulate air (HEPA) filters and mixed combustible wastes are the most difficult wastes to treat because of their heterogeneous makeup.

2.2 RECOMMENDATIONS OF TREATMENT ALTERNATIVES FOR DEMONSTRATION AND DEPLOYMENT

- Supercompaction is available commercially and has exhibited a good overall ranking. Adopt this method if it can reasonably be determined that the resulting waste forms are acceptable. However, with the current uncertainties in waste form requirements, it is prudent to have other technology available to produce higher-quality waste forms.
- The arc pyrolysis and melting process is also a very attractive alternative because it can handle all of the wastes in one unit and give high volume reduction with good quality waste forms. Because the process is not well known, confirm its feasibility to determine the limits of its application and its ability to process all of the wastes in future applications. If its feasibility is confirmed, strongly consider its demonstration for TRUW treatment applications.
- One of the variants of the maximum volume reduction (MVR) alternative should be developed, because it appears to offer the most potential for successful improvement of the treatment system and thus should be the prime candidate for further development. It offers the best system economics and will produce higher quality waste forms. Because it employs multiple processing steps, it has significant flexibility and the ability to further tailor the final waste form. For this alternative, treatment of previously cemented wastes should be avoided if possible; decontamination of metals is of marginal value; and oxide melting is preferred over cementing.

2.3 RECOMMENDATIONS FOR FUTURE WORK AND EVALUATION

- Begin accelerated testing and demonstration of the arc pyrolysis and melting alternative. Identify in greater detail the capabilities, limitations, waste form quality, costs, and risks associated with the process.
- Test, evaluate, and/or develop a system for separation of waste forms, an incinerator, a metal melter, and an oxide and residue melter for the MVR alternative.
- Demonstrate the arc pyrolysis and melting and the MVR alternatives in parallel paths until one is clearly shown to be superior and adequate.
- Carefully consider the design and use of HEPA filters and facility off-gas systems as ways to reduce the volume of waste generated and to simplify waste treatment.
- Update this analysis as more information becomes available on disposal requirements, waste forms and volumes, and behavior of treatment processes.

3.0 STUDY APPROACH

This study is the first step in the development of an integrated TRUW treatment technology for current commercial wastes and wastes that will be generated during the consolidation of fuel rods from commercial spent fuel assemblies.

The various steps used for the potential development and application of treatment technology are illustrated in Figure 3.1. Following this treatment analysis, development and demonstration activities are identified for the key elements of the preferred alternatives. These activities include early development of selected treatment alternatives and more detailed evaluation of specific processes for the selected alternatives. For example, if separation of HEPA filters into their various components is selected, then it would be necessary to review and develop several of the various separation methods identified in Section 6.0. Concurrent with this development, waste forms (from the treatment processes) would be characterized and evaluated during the early process development period [(i.e., to meet production needs and waste acceptance criteria (WAC)]. Following these activities, the selection of each of the specific technologies would be made, and pilot-scale processes would be demonstrated using both nonradioactive and radioactive materials. The technology would then be ready for deployment.

The schedule for these activities is short with MRS milestones for the selection of the treatment alternative in March 1987, for submittal of a license application in January 1989, and for equipment to be designed and installed for the prototype tests of the consolidation equipment in March 1990 (U.S. DOE 1985c).

This study followed the steps identified in Figure 3.2. The first step was to identify the study bases, described in Section 4.0. Information from the various sources of commercial waste and the current MRS facility design was obtained and integrated into the waste-generation data provided in Section 5.0. The possible treatment alternatives for each of the waste types were examined (see Appendix A), and eight alternative waste treatment objectives and processes were identified (see Section 6.0). Available information was then

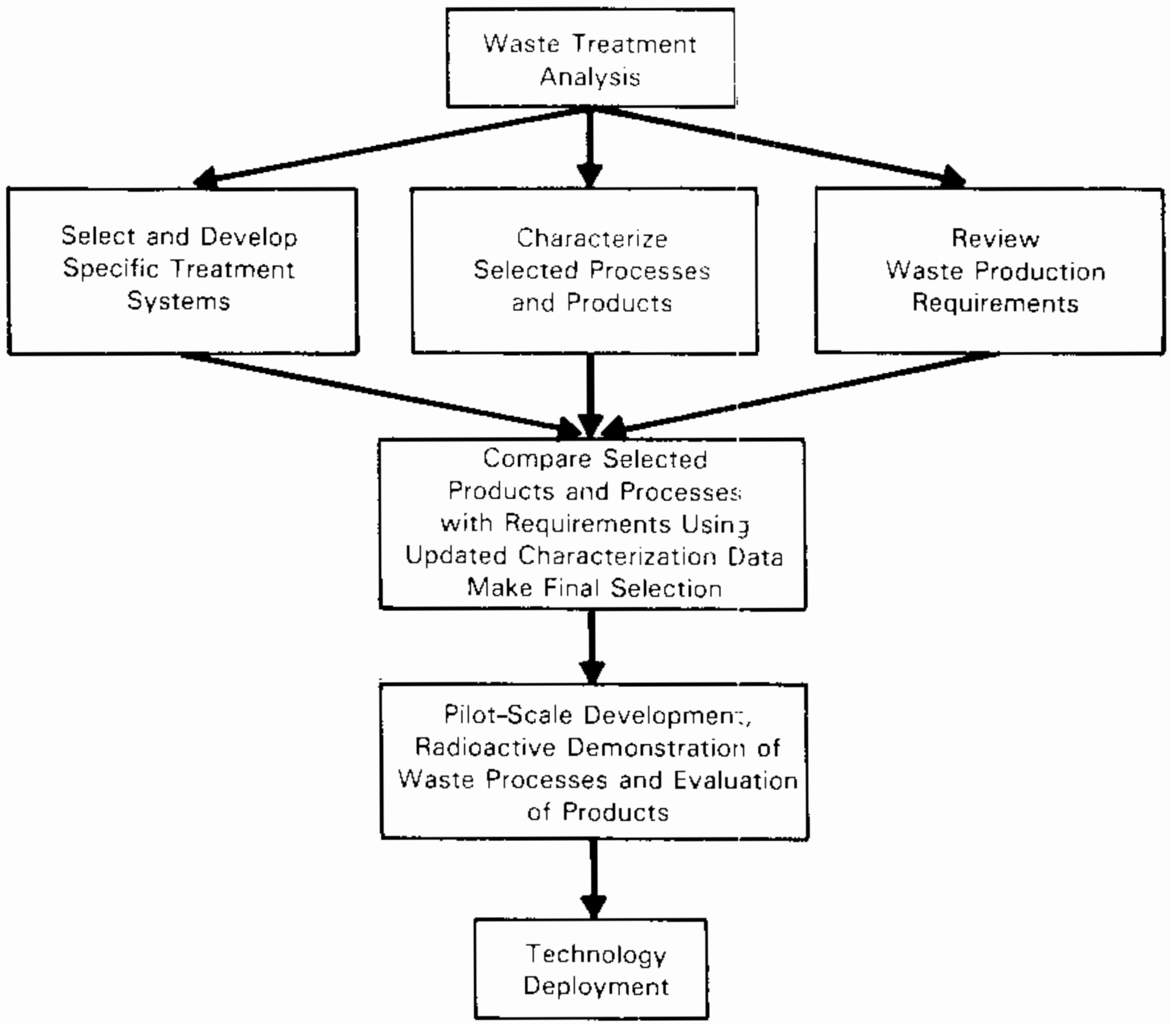


FIGURE 3.1. Steps of the Planned Development and Application of Treatment Technology

used to calculate the volumes of treated waste to define the waste forms that would be generated by the alternative treatment processes (see Section 6.0).

The treated waste volumes are the key factors in determining transportation and disposal costs, and also impact the process equipment requirements and processing costs given in Section 7.0. The waste forms postulated to be generated from all of the treatment alternatives and the unit processes to be used in the alternatives were identified, rated, and compared (see Sections 8.1 and 8.2).

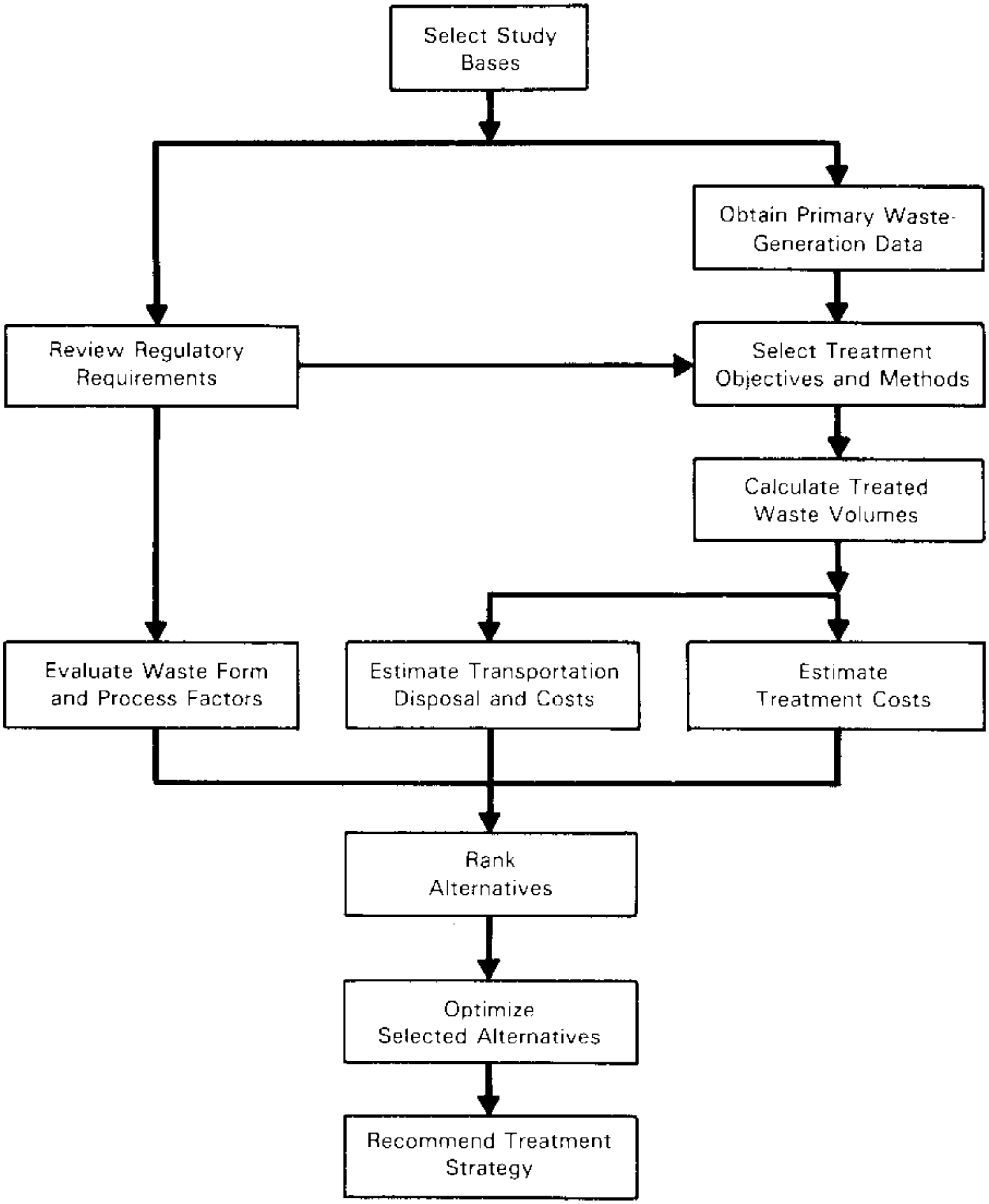


FIGURE 3.2. Flow Chart for TRUW Treatment Study

4.0 STUDY BASIS

This section identifies the major technical bases and assumptions used in the study and the regulatory background for this study. The bases were applied to the overall study approach described in Section 3.0 and were used to develop the detailed data and analyses presented in the subsequent sections.

4.1 TECHNICAL BASES AND ASSUMPTIONS

The major technical bases and assumptions used in the study are given below.

- The wastes are assumed to be processed at a central treatment facility. This includes wastes from an MRS facility or from the front-end spent fuel handling and treatment facility at a geologic repository, and TRUW from other commercial activities. The treated TRUW and HAW are shipped by rail to a geologic repository, and the LLW (if generated) is shipped by truck to a shallow land burial ground.
- The MRS facility is the reference central treatment facility for this study. The intact spent fuel assemblies are received at the MRS facility, where they are disassembled and the consolidated spent fuel rods are packaged into canisters. The filled canisters are either sent to in-cell lag storage, loaded into rail transportation casks and transported to a repository, or placed in sealed concrete storage casks on an outside storage pad, pending shipment.
- The central treatment facility is assumed to process 70,000 MTU of spent fuel at a rate of 3,000 MTU/yr for 23.3 years. The facility also receives TRUW from other commercial facilities during this time.
- The quantities and characteristics of repository-bound wastes from the central treatment facility were derived from the conceptual design report on the MRS facility (Parsons Co., Westinghouse Electric Corp. and Golder Associates 1985a, 1985b). These wastes are assumed to result from the consolidation of spent nuclear fuel, which has an

average integrated exposure of 33,000 MWd/MTU and has been aged 10 years since being discharged from the reactor.

- The quantities and characteristics of offsite commercial TRUW received at the central treatment facility are based on unpublished estimates by PNL staff. The TRUW estimatec to be backlogged in 1998 from these commercial facilities [e.g., racioisotope generators and users, research and development (R&D) laboratories, nuclear power reactors, decommissioning of fuel fabrication facilities, etc.] are to be received and processed during the first 10 years. The commercial wastes, generated and received annually after the initial wastes are processed, are assumed to be of the same types and quantities as the backlogged waste.

- Remote-handled wastes generated or received at the MRS facility are assumed to be TRUW and HAW, which are to be disposed of in a deep geological repository. One quarter of the CH wastes generated at the MRS facility are assumed to be TRUW; the other three quarters are assumed to be LLW, which are not considered further in this study. The management of all secondary wastes resulting from any of the treatment schemes evaluated in this study is considered, even if they are LLW.

- Management of the TRUW considered in this study begins with the pretreatment and continues through treatment, canister filling, certification, final four-month lag storage, and transportation to, and emplacement in, a disposal facility. The front-end handling activities (i.e., receiving and unloading, front-end lag storage, and gross sorting into CH and RH and general waste types) are not considered in this study.

- The definition of TRUW here is from the Environmental Protection Agency's (EPA's) final rule 40 CFR 191 (U.S. EPA 1985b): "'Transuranic radioactive waste,' ... means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years ...."

- Transuranic waste and HAW considered here are assumed to be disposed of concurrently with spent fuel and HLW in a deep geologic repository in the western part of the United States. Thus, the impacts of various TRUW and HAW treatment strategies on waste disposal thus are incremental to the disposal of the spent fuel and HLW.
- Detailed waste form and packaging requirements for disposal at a geologic repository are a primary basis, but are still unknown. The treatments studied provide a broad range of waste form characteristics. Final waste canister designs may also vary.
- All cans of repository-bound wastes from the central treatment facility undergo inspection, assay, certification, and labeling.
- All costs are in unescalated 1985 dollars.
- Capital, operating, and decommissioning costs of the waste treatment facilities were estimated by the authors and based in part on McKee et al. (1984), Ross et al. (1985), and Parsons Co., Westinghouse Electric Corp. and Golder Associates (1985a). Research and development costs were not evaluated.
- Only one transportation system is defined and used for treated TRUW and HAW and secondary LLW resulting from TRUW and HAW treatment. The transportation system and its costs are those used by DOE (1986c).
- Repository disposal costs are based on a previous study (Ross et al. 1985), which used information derived from the Repository Economics (RECON) model (Clark, Schutz and Luksic 1985) for a repository in basalt rock. Costs for disposal of the secondary LLW are determined using the cost schedule dated July 15, 1985 (Chem-Nuclear Systems, Inc. 1985).

4.2 REGULATORY BACKGROUND

The decision on the methods for disposal of TRUW and HAW have not been made, and detailed requirements have not been established. However, the final treated waste form and its canister will have to meet federal regulations for interim storage, transportation, and ultimate disposal. This section summarizes the major regulations for TRUW and HAW management with respect to their potential impact on the selection of TRUW and HAW treatment strategies and subsequent waste management steps.

4.2.1 Generally Applicable Regulations

The basic federal regulation for environmental radiation protection for the operation of uranium nuclear fuel cycle facilities is stated in 40 CFR 190 (U.S. EPA 1985a). This regulation applies to the waste management steps of waste generation, treatment, and storage, and the filling and presealing of waste disposal repositories, but it does not apply to the disposal period. The basic federal regulation for radioactive waste disposal is stated in 40 CFR 191 (U.S. EPA 1985b).

The basic NRC regulation, "Standards for Protection Against Radiation," is stated in 10 CFR 20 (U.S. NRC 1984a). This regulation gives some dose limits and refers to 40 CFR 190. The 10 CFR 20 regulation also states that anticipated doses should be reduced to as low as reasonably achievable (ALARA).

The basic regulations regarding protection of the public against radiation during transportation of radioactive materials are also covered in 10 CFR 20. Specific regulations have been issued by the U.S. Department of Transportation (DOT) in 49 CFR 171-174, 177, and 178 (U.S. DOT 1984) and by the NRC in 10 CFR 71 (U.S. NRC 1984d). These latter two regulations specify packaging requirements, radiation limits, labeling requirements, handling procedures, and security procedures. The principal performance requirement for transportation of TRUW and HAW is for containment, which is generally provided by the outer transportation packaging [i.e., the cask for RH-TRUW, or the Transuranic Package Transporter (TRUPACT) packaging for CH-TRUW].

4.2.2 Regulations Related to Release Rates from Repositories

Detailed regulations and requirements for commercial TRUW and HAW forms are not yet available. However, some regulations have been developed for HLW [10 CFR 60 (U.S. NRC 1984b) and 40 CFR 191] and LLW [10 CFR 61 (U.S. NRC 1984c)]. The Nuclear Waste Policy Act of 1982 (NWPA) provides direction for the disposal of HLW and spent fuel, but does not specifically address TRUW. However, RH-TRUW could be interpreted as HLW in the NWPA by the following definition of HLW: "other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation." Detailed requirements and specifications have been prepared for TRUW, generated by national defense programs, that is to be sent to the Waste Isolation Pilot Plant (WIPP) (Westinghouse Electric Corp. 1984).

In anticipating waste form requirements for commercial TRUW and HAW, a range of possibilities has been considered. The minimum requirements will likely be those that are applied to wastes going to the WIPP and/or those for commercial LLW Class C. The maximum requirements would be those applied to commercial HLW if TRUW and HAW are disposed of in a commercial geologic repository. This section identifies all of the potential requirements that could be applicable to TRUW and HAW forms and canisters. Table 4.1 has been constructed to provide a perspective of the potential disposal requirements for TRUW and HAW. It is recognized that some of the requirements (e.g., those for subsidence on the LLW site) may not be applicable to deep geologic repository disposal. Therefore, strategies have not been selected for evaluation based solely on their ability to meet the most stringent requirements. A brief discussion of the waste form requirements as they relate to release rates from repositories is provided in the following subsections.

EPA Requirement for TRUW

Regulation 40 CFR 191 specifies the minimum concentrations of radionuclides in radioactive waste required to classify it as HLW. These values are identical to the maximum limits for waste acceptable for shallow land burial, provided in 10 CFR 61, and also include some radionuclides not specifically identified in 10 CFR 61. However, note that 40 CFR 191 deletes a table in prior drafts that gave numerical concentrations for classifying HLW.

The EPA requirements for disposal of TRUW and HLW do not directly state waste form or canister requirements; instead, they specify the limits in terms of the amounts of TRUW constituents that can be released to the accessible environment over a period of 10,000 years per 1 million curies of TRU nuclides present in TRUW.

TABLE 4.1. Summary of the Regulations/Criteria Related to TRUW and HAW Form/Canister Requirements

No.	Characteristic	Requirements Source	Composite Bases from 10 CFR 60 and 61, 40 CFR 191, WIPP, and WAPS[a]
1	Canister	WIPP	Noncombustible; >21-yr life
		10 CFR 61	300-yr life with poor waste forms (see "other" below); pass Type A transportation requirements; maintain containment during transportation, emplacement, retrieval
		WAPS	Austenitic stainless steel
2	Package characteristics	10 CFR 60	Chemical-physical-nuclear characteristics compatible with repository; 300- to 1,000-yr life after repository closure
3	Package considerations	10 CFR 60	Solubility; oxidizing/reducing potential; corrosion; hydriding; gas generation; thermal loads and effects; stress, radiolysis; retardation of radionuclide migration; leaching; fire/explosion hazards; synergistic interactions
4	Waste form	10 CFR 61	If no 300-yr container the waste form must be resistant to radiation (10^8 Rad, γ); resistant to biodegradation test, leaching, breakdown from water immersion, and breakdown from thermal cycling test; and have compressive strength >50 psi
		10 CFR 60	Not dispersible; particles to be consolidated
		WIPP	<1%/can can be <10 μm particles
		WAPS	No organics allowed
5	Waste form combustibility	10 CFR 60	Must be noncombustible unless shown that fire will not compromise safety
		WAPS	Must be noncombustible
		BWIP	No organics allowed
6	Free liquid content	10 CFR 61	<0.5 wt%; need double the minimum amount of absorbent
		WIPP	Sludges OK if canister is corrosion-protected
		WAPS	None that affects containment for 1100 years
7	Explosives content	WIPP	None allowed
		WAPS	Must be nonexplosive
8	Toxic gases, vapors	10 CFR 61	None allowed except for gaseous radionuclides
9	Pyrophoric material content	10 CFR 61	None allowed
		WIPP	Allowed only if intimately associated with radionuclides; pyrophorics must be <1 wt% of waste
		WAPS	Must be nonpyrophoric
10	Gaseous waste	10 CFR 61	Pressure <1.5 atm at 20°C; <100 kg/m^3 in other containers
		WAPS	None except cover gases and radiogenic gases
11	Gas generation	WIPP	<220 kg/m^3 organic in 208-L gal drums; <100 kg/m^3 in other containers
12	Hazardous, biologically pathogenic, infectious material	10 CFR 61	Reduce nonradiological hazard to as low as practicable; see #18 below for branch position paper requirements for LLW

TABLE 4.1. (contd)

No.	Characteristic	Requirements Source	Composite Bases from 10 CFR 60 and 61, 40 CFR 191, WIPP, and WAPS[a]
13	Structural stability	10 CFR 61	Form or container must be structurally stable in disposal environment; see also branch position paper for LLW below (#18)
		WAPS	Canister must withstand 9-m drop without breaking
14	Void spaces	10 CFR 61	Reduce to extent practical
		WAPS	Must be less than 20% of internal volume
15	Release rate from repository to environment	40 CFR 191	Probability <0.1 that release values in 10,000 years will exceed those in EPA table
		10 CFR 60	From engineered barrier, $<10^{-5}$/yr of 1,000-yr inventory; not applicable to radionuclides released <0.1% of calculated total release rate
16	Dose to public	40 CFR 191	For 1000 years, <25/75 mrem/yr + ALARA; <4 mrem/yr from βγ and <15 mrem from alpha radionuclides in aquifer
17	Identification	10 CFR 60	Permanent and unique
18	Other	10 CFR 61	Branch technical position paper (U.S. NRC 1983a) gives details on waste form requirements: compressive strength >50 psi per ASTM C39 after all tests: - Expose to 10^8 Rad - Resistant to biodegradation test (ASTM G21&22) - Resistant to 90-day leak test (leachability index >6 per ANS 16.1) - Resistant to immersion 90 days - Resistant to thermal cycling +60 to -40C, 30 times (ASTM B554, Section 3) - Destructive analysis to assure homogeneity Or for 300-yr container: - Strength with 120 lb/ft^3 overburden - Resistant to 10^8 Rad - Resistant to biodegradation test as above - Resistant to thermal cycling as above - Contents inspectable - Passive vent - Withstand 3-G lifting load
		WIPP	CH <3.5 W/m^3; RH <300 W/can; <200 g fissile/208-L gal drum; CH <200 mrem/hr; RH <100 rem/hr; <5 g/ft^3 fissile RH

(a) WAPS = Waste Acceptance Preliminary Specifications for West Valley Demonstration and Defense Waste Processing Facility High-Level Waste Forms (U.S. DOE 1986b, 1986c).

Essentially all of the activation products in irradiated fuel hardware eventually are in the TRUW and HAW. Carbon-14 is the only activation product that appears in the EPA list of specific isotopes of concern; thus all other activation products can be put into the EPA category of all other non-TRU nuclides. The EPA limit for releases of these other non-TRU nuclides is the same as for the fission products cesium-135, cesium-137, strontium-90, and tin-126.

NRC Requirements for TRUW

The NRC has not developed regulations or disposal requirements, specifically for TRUW forms, but their HLW regulations in 10 CFR 60 are stated to be applicable to all radioactive wastes that are disposed of in a geologic repository. The supplementary information, for 10 CFR 60.113 (U.S. NRC 1983a), emphasizes that release rate limits apply to all radionuclides that are disposed of in a geologic repository and specifically includes those from TRUW.

Regulation 10 CFR 60 states that containment within the waste packages must be substantially complete for a period of at least 300 to 1,000 years after closure of a repository. In addition, the release rate from the engineered barrier system (which includes any canister, overpack, and backfill materials) shall not exceed 1 part in 100,000/yr of the inventory of each radionuclide calculated to be present at 1,000 years following permanent closure. (This limit does not apply to any radionuclide that is released from the engineered barrier at a rate of less than 0.1% of the calculated total release rate limit.)

Requirements for Release Rates from Waste Forms

Requirements for the fractional release rate limits for releases specifically from the waste forms cannot be obtained directly from the existing NRC or the EPA regulations, because the EPA regulations specify maximum releases to the accessible environment, and the NRC regulations specify maximum releases from the engineered barrier system in the repository. Thus, allowable release rates are related to the combined performance of a number of barriers and may not necessarily be directly related to waste form durability.

Repository Waste Acceptance Requirements

Draft HLW acceptance requirements for the Basalt Waste Isolation Project (BWIP) have been developed and provide some additional indications of requirements for the waste going to the repository. In its concern for the potential for organic complexes forming in the repository and enhancing the migration of actinides, BWIP has included in its requirements the following: "The waste form and the internal volume of the waste form container shall not contain organic materials" (Randklev 1983). Thus, if the TRUW were to go to the BWIP or other repository with this requirement, it may well be expected that the TRUW would have to meet this requirement as well.

On a generic basis, the DOE has proposed preliminary HLW acceptance requirements that would meet the anticipated requirements for disposal in a waste repository in salt, basalt, and tuff (U.S. DOE 1986c, 1986d). These preliminary requirements, which provide guidance in the evaluation of waste forms, are based on draft requirements previously developed specifically for a basalt, tuff, or salt repository.

4.2.3 Regulations Related to Other Waste Form Characteristics

Other considerations related to waste form characteristics are given in the composite of waste form/canister characteristics shown in Table 4.1. In addition to release rates, the waste form characteristics are related to the following:

- canister and other package aspects[(a)]
- particulate content
- free liquid content
- combustibility (organic content)
- pathogenic and infectious material content[(a)]
- void spaces
- radiation resistance
- thermal cycling resistance
- toxic vapor content
- explosive and pyrophoric material content
- gaseous radionuclide content
- gas generation rate
- structural resistance
- overall leach resistance
- homogeneity

(a) Not directly of interest in this study.

The considerations in Table 4.1 are based primarily on the assumption that minimum requirements for TRUW would be somewhat equivalent to those of HLW and

LLW Class C. Additional considerations are those in 40 CFR 191 for TRUW, the draft WAPS for the West Valley Demonstration and Defense Waste Processing Facility High-Level Waste Forms (U.S. DOE 1986c, 1986d), the WIPP WAC for defense TRUW (Westinghouse Electric Corp. 1984), and the draft HLW acceptance requirements for BWIP (Randklev 1983).

Some of the requirements given in Table 4.1 are related to the canister or waste package characteristics. However, 10 CFR 61 states that for LLW, high integrity canisters can be used to substitute for some of the required characteristics of waste forms. Although this potential is recognized, the evaluation of canister characteristics is not within the scope of this study.

4.2.4 Waste Form Characteristics for Evaluation

From the above reviews of the waste form requirements, characteristics were selected for evaluation for each of the waste forms that resulted from the treatment alternatives. These characteristics include: release rate, organic or combustible content, immobilized particulates, pyrophoric potential, structural stability, and radiation resistance. Details of the evaluation method and its results are in Section 8.1.

5.0 DEFINITION OF INITIAL OR UNTREATED WASTE STREAMS

The majority of the wastes considered in this report are those expected from a central treatment facility, such as an MRS facility (or a repository receiving and handling facility), which may consolidate the spent fuel assemblies and possibly store them for a period of time before they are disposed of in a selected repository. There are also several additional sources of commercial TRUW, including the West Valley Demonstration Project, nuclear power reactors, several decontamination and decommissioning operations for past plutonium fuel production, and commercial operations that generate and use isotope sources.

For this assessment it was assumed that all of the wastes would be treated and prepared in a central facility. This seems reasonable because the facility will produce a large fraction of the wastes and will need to have systems to treat its wastes. It generally would not be reasonable or economical for the numerous other waste producers to have treatment capabilities for their smaller amounts of wastes. The untreated waste volumes in this report represent the waste volumes from the process cells of an MRS facility. Because the spent fuel hardware will be shredded in the process cells to aid handling, its volume is calculated based on its shredded volume. The volume of the HEPA filters, which are not treated in the process cells, represents the actual volume of the HEPA filters.

5.1 WASTES FROM SPENT FUEL ROD CONSOLIDATION OPERATIONS

At the MRS facility (or the repository receiving and handling facility) spent fuel assemblies are received from nuclear power plants by truck or rail and taken into a processing cell where the fuel rods are removed from the remaining fuel assembly hardware. The massive pieces of residual hardware are loaded directly into the drum, and the remaining materials are sent through a shredder to facilitate handling and to reduce their volume. This hardware is a major waste stream from the consolidation operation.

During the rod removal operation, most of the rods are expected to be removed intact. However, some of the rods may have failed (or may fail during removal) and may release some spent fuel particles to the hot cell and its ventilation system. The HEPA filters used in the ventilation system of the consolidation process collect radioactive material and are the major waste stream (by volume). Additional wastes are generated from decontamination activities and other cell maintenance operations. Table 5.1 shows the volumes of waste anticipated from all of these operations at the MRS facility (or repository receiving and handling facility) and the distribution between remote-handled (RH) and contact-handled (CH) wastes. This distinction is important in determining the characteristics of the processing facility.

This report uses the volumes and weights of waste estimated for an MRS facility (Parsons Co., Westinghouse Electric Corp. and Golder Associates 1985b) as a basis for estimating untreated waste volumes. The waste volumes are adjusted for a processing rate of 3,000 MTU/yr of spent fuel. The current information from the MRS facility design has not divided the wastes into LLW and TRUW. Therefore, we have assumed that all of the RH wastes and one quarter of the CH wastes will be disposed of in a geologic repository. This is consistent with early estimates in the MRS Study (Parsons Co., Westinghouse Electric Corp. and Golder Associates, 1985c) and the estimates from the Barnwell Nuclear Fuel Plant (BNFP) waste generation studies (Carr et al. 1982).

TABLE 5.1. Projected Annual Untreated Waste Volumes from Spent Fuel Rod Consolidation[a]

Waste Type	RH Wastes, m^3	CH Wastes, m^3
HEPA Filters	786	12
Spent Fuel Hardware[b]	450	--
Failed Equipment	0	1
Combustibles	5	6
Solutions and Sludges	3	2
Totals	1,244	20

(a) Based on consolidation of 3000 MTU of intact fuel.
(b) The hardware is shredded as part of the disassembly process.

We have not considered the costs of treatment, transportation, or disposal of the LLW. It may be desirable to treat some of the LLW in the same process systems as the TRUW to achieve volume reduction and cost savings. The LLW must not be contaminated with sufficient TRU to change it into TRUW.

5.2 EXISTING AND PROJECTED COMMERCIAL TRUW

Previous commercial activities in reprocessing, plutonium handling, fuel fabrication, and use of radioisotopes have generated and will likely generate additional TRUW before 1998, the startup year for a planned commercial repository. Table 5.2 summarizes the types of waste and estimates of their cumulative volumes in 1998. As with the fuel consolidation wastes, the wastes are generally "untreated" and they are in 208-L or similar-sized drums. They may or may not meet disposal criteria, and they may or may not have gone through some volume reduction process at the source. Most of the waste types given in Table 5.2 are self-explanatory. Combustibles are considered to be totally combustible but may contain a fraction of plastics, including polyvinyl chloride (PVC). The mixed combustibles are a mixture of metals, oxides, and combustible materials. Resins are considered to be primarily organic but may contain a fraction of zeolites, which are inorganic noncombustibles. Since it

TABLE 5.2. Total Existing and Projected Untreated TRUW Volumes to 1998 from Various Commercial Sources[a]

Waste Type	RH Wastes, m^3	CH Wastes, m^3
HEPA Filters	--	71
Failed Equipment	272	1,116
Combustibles	--	334
Mixed Combustibles	655	712
Resins	7	--
Cemented Wastes	587	467
Cement Rubble and Soil	388	--
Totals	1,909	2,700

(a) Waste volumes packaged at the source.

will be difficult or impossible to ship liquid wastes, all liquids are assumed to be cemented at their point of generation before their shipment to the central treatment facility. The cement rubble and soil are assumed to result from decommissioning activities. The major source of wastes is expected to be the West Valley Demonstration Program and its HLW solidification activities. The volumes of TRUW expected from West Valley are taken from their Environmental Impact Statement (U.S. DOE 1982).

5.3 ADDITIONAL GENERATION OF TRUW

Continuing activities at reactors and the sales and usage of isotopes are expected to generate some TRUW as shown in Table 5.3. These small volumes are included to provide a best estimate of total waste volume. Contact-handled cemented wastes comprise most of the total.

TABLE 5.3. Projected Annual Generation Rate of Commercial TRUW After 1998[a]

Waste Type	RH Wastes, m^3	CH Wastes, m^3
Failed Equipment	--	4
Combustibles	--	13
Cemented Wastes	0.5	25
Totals	0.5	42

(a) Waste volumes packaged at the source.

5.4 VOLUME OF WASTES FOR TREATMENT IN A CENTRAL TREATMENT FACILITY

The volumes of wastes in Sections 5.1 and 5.3 are annual generation rates, but the volumes in Section 5.2 are total accumulated volumes up to 1998. The TRUW expected up to 1998 were assumed to be treated over a 10-yr period. It is assumed that beyond the year 2008 additional commercial TRUW will be generated beyond that projected in Table 5.3 and will require treatment. Therefore, we have used a constant process rate for the facility life. Totaling the volumes in Tables 5.1 and 5.3 with 10% of the volumes in Table 5.2 results in the volumes shown in Table 5.4, which represent the annual processing rates used in

TABLE 5.4. Projected Annual Volumes of Waste to be Treated in a Central Treatment Facility[(a)(b)]

Waste Type	RH Wastes, m^3	CH Wastes, m^3
HEPA Filters	786	19
Spent Fuel Hardware (shredded)	450	--
Failed Equipment	27	116
Combustibles	5	52
Mixed Combustibles	66	71
Resins	2	--
Solutions and Sludges	3	2
Cemented Wastes	59	72
Cement Rubble and Soil	--	39
Totals	1,398	371

(a) Volumes before packing for transportation.
(b) Assumes that accumulated commercial wastes existing in 1998 are processed over a 10-yr period.

the balance of the study. A comparison of Tables 5.1 and 5.4, shows that a central treatment facility would receive about 10% more RH waste, and about 18 times more CH-TRUW than a facility that only treated the spent fuel consolidation wastes. Table 5.4 shows that the HEPA filters are the largest waste volume, with spent fuel hardware being the second largest waste volume. This results in part from no pretreatment of the HEPA filters and the pretreatment of the spent fuel hardware by shredding. Note that the combined RH waste volume is about four times greater than the combined CH waste volume. This relationship is also typical of projected reprocessing waste volumes (Ross et al. 1985), but is opposite from that which occurs in the defense waste processing, where the CH wastes greatly overshadow the RH wastes (U.S. DOE 1984).

6.0 WASTE TREATMENT PROCESSES AND THEIR WASTE QUANTITIES

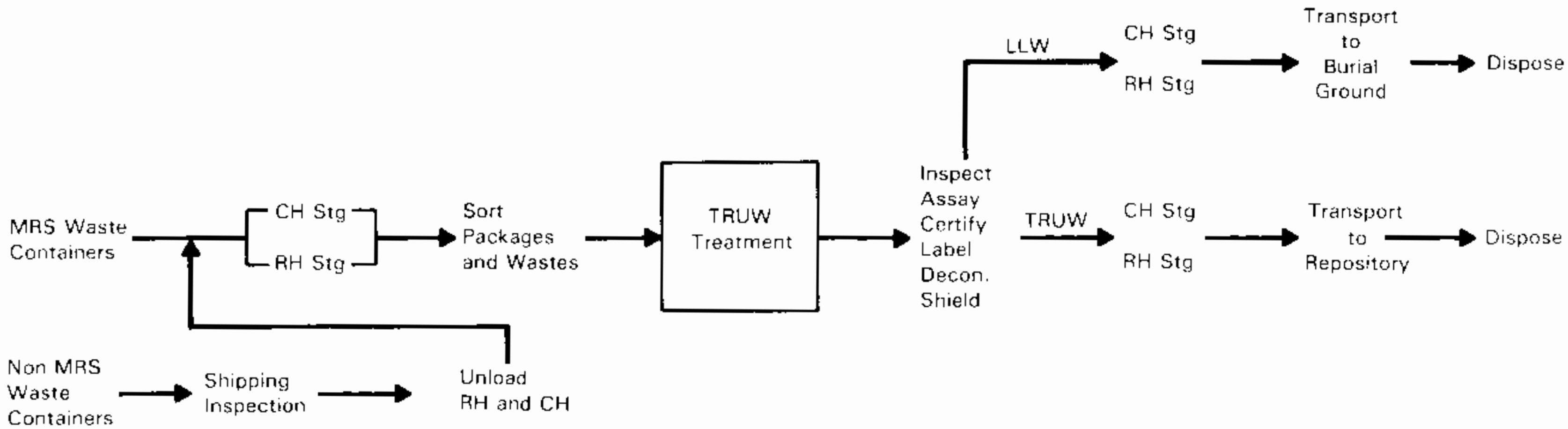
The types of waste (CH and RH), waste treatment objectives, viable treatment methods, and characteristics of the resulting waste forms were considered in the selection of waste treatment process alternatives and are discussed in this section. The treatment process was selected from the alternative treatment processes for each type of waste. The treatment processes are described in Appendix A.

The major objectives in the treatment of wastes are low cost, small volumes, processing safety, and acceptable waste form quality. In this study, the costs are for the total system and are a mixture of treatment, transportation, and disposal costs that often work against each other. For example, volume reduction will decrease both transportation and disposal costs, frequently at the expense of additional treatment costs. Because acceptable waste form quality is not yet defined, we identified and examined eight alternatives that provide a range of economics and waste form quality.

A process flow diagram has been developed for each selected waste treatment process alternative. Each flow diagram shows the division between the CH and RH wastes and where the RH and CH wastes should be combined into one process unit. (This combination always requires that the CH wastes be treated using the RH equipment. This should only be done where either the waste volumes are very low or where the CH wastes would not be severely contaminated and would not require remote handling following processing.)

The spreadsheets for calculation of the treated waste volumes generally show three-place accuracy, but the precision of the input data is more like ±20%. Additional significant figures are shown to avoid further loss of precision in subsequent calculations.

Figure 6.1 depicts the overall TRUW processing operations. The wastes come from two major sources: the spent fuel rod consolidation and the external commercial waste generators. The block labeled "TRUW Treatment" represents the different treatment alternatives discussed in the Subsections 6.1 through 6.8. The operations such as assay, inspection, decontamination, welding, and



Note: CH Stg = Contact-Handled Storage
RH Stg = Remote-Handled Storage

FIGURE 6.1. Overall Waste Processing Flow Diagram

shipment shown in this figure are considered to be common to all of the treatment alternatives. However, recognize that the volumes and types of waste that will require processing through the operations will depend strongly on the treatment processes selected. No consideration has been given to the possible conversion of CH wastes to RH wastes due to the higher dose rates resulting from volume reduction. A previous study (Ross et al. 1985) indicated this was of minor importance.

6.1 ALTERNATIVE 1--NO TREATMENT

Alternative 1 minimizes the treatment steps by packaging the TRUW as-generated or as-received at the central treatment facility. This alternative is expected to have the lowest waste form quality and high disposal and transportation costs, but treatment costs, except for canisters, will be low.

Because the wastes are packaged as-generated, a variety of canister sizes is required. Canister sizes are dictated by the dimensions of the original wastes. Our expected canister sizes are shown in Table 1 with the waste volume and weight calculations. For example, we have defined a 3,000-L container (0.91-m-dia and 4.6-m-long) to allow for direct disposal of HEPA filters without treatment. Failed equipment is considered to be size-reduced in the facility so that it can fit inside 1280-L container (a "standard" schedule 10, 24-in.-dia (0.61 m) pipe, 4.6-m long). Two-hundred-eight-liter drums are used for most CH wastes and are expected to be the size of waste containers for the spent fuel hardware that will be shredded in the processing facility.

The basic input data on waste generation is in terms of volume. The untreated weight or untreated density are estimated in this study from the general literature. Then, either the untreated weight or untreated density is calculated from the volume. There is a general assumption that the waste drums are only filled to 90% of their volume capacity. This 90% factor has been used in calculating the treated volume in Table 6.1 and other similar tables in this section. If materials (such as the spent fuel hardware or failed equipment) are prepackaged in the process or if materials (such as the cemented wastes) are shipped to the facility already drummed, then the original volumes are

TABLE 6.1. Annual Treated Waste Volumes, Weights, and Number of Packages for No-Treatment Alternative (1)

Wastes	Volume, m^3 Untreated	Volume, m^3 Treated	Weight, kg Untreated	Weight, kg Treated	Density, kg/m^3 Untreated	Density, kg/m^3 Treated	Number of Packages 208L	303L	1280L	3000L
RH Wastes										
Failed Equipment	27	27	8,640	8,640	320	320			21	
Spent Fuel Hardware	450	450	405,000	405,000	900	900	2,163			
HEPA Filters	786	1,257	126,000	126,000	160	100				419
Filters and Mixed Combustibles	66	73	19,800	19,800	300	300			57	
Combustibles	5	5	1,135	1,135	250	250			4	
Resins	2	2	2,000	400	1,000	1,000	11			
Solutions and Sludges	3	4	2,800	5,661	1,100	1,600	19			
Cemented Wastes	59	59	94,400	94,400	1,600	1,600	284			
Totals	1,397	1,880	649,000	660,000			2,477	0	82	419
CH Wastes										
Failed Equipment	116	116	37,100	37,100	320	320	558			
HEPA Filters	19	38	3,100	3,100	180	82		125		
Filters and Mixed Combustibles	71	79	21,300	21,300	300	300	379			
Combustibles	52	57	12,920	12,900	250	250	276			
Solutions and Sludges	2	3	2,200	3,670	1,100	1,600	12			
Concrete Rubble	39	39	49,300	49,300	1,270	1,270	188			
Cemented Wastes	72	72	115,000	115,000	1,600	1,600	364			
Totals	371	404	241,175	242,642			1,759	125	0	0

Note: Data and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

still used, and no packing factor is applied. Package size is determined from the original size of the wastes as noted above. Finally, the number of waste packages is obtained from the treated volume and the package size. The calculations are totaled to determine the total volumes of waste and the number of waste packages of each specific size, and the data are maintained separately for CH and RH wastes except where they may be combined for a few specific cases.

The data in Table 6.1 shows the large volume and the high number of canisters that will be produced without waste treatment. The HEPA filters are the largest volume of waste because they have a poor packing factor within the containers, and spent fuel hardware is the second-largest volume. Resins are dried and solutions and sludges are cemented as indicated in Figure 6.2. This should be considered the minimum processing that would be acceptable for transportation and disposal. The solutions and sludges are assumed to be 75% water and 25% solids and based on a 60 wt% liquid waste loading in cement.

6.2 ALTERNATIVE 2--MRS REFERENCE

As far as possible, this alternative duplicates the treatment currently planned for the proposed MRS facility, except that the MRS facility as currently planned will not receive or process other commercial wastes. The primary basis for selection of the waste forms for this alternative was the WIPP WAC. No effort is made to eliminate combustibles or particulates in the final waste forms. This alternative provides some volume reduction through the use of HEPA filter disassembly and compaction of the frames and media.

The MRS facility designers recognized that significant reduction of waste volumes generated within the facility was possible and considered the processes identified in Figure 6.3. Like in all of the other alternatives, the spent fuel hardware is pretreated by shredding. All wastes are packaged in 208-L drums. In the MRS facility design, five of the RH drums are stacked into a single framework for handling and compatibility with the consolidated spent fuel canisters. Having all of the packages the same length should simplify the subsequent handling.

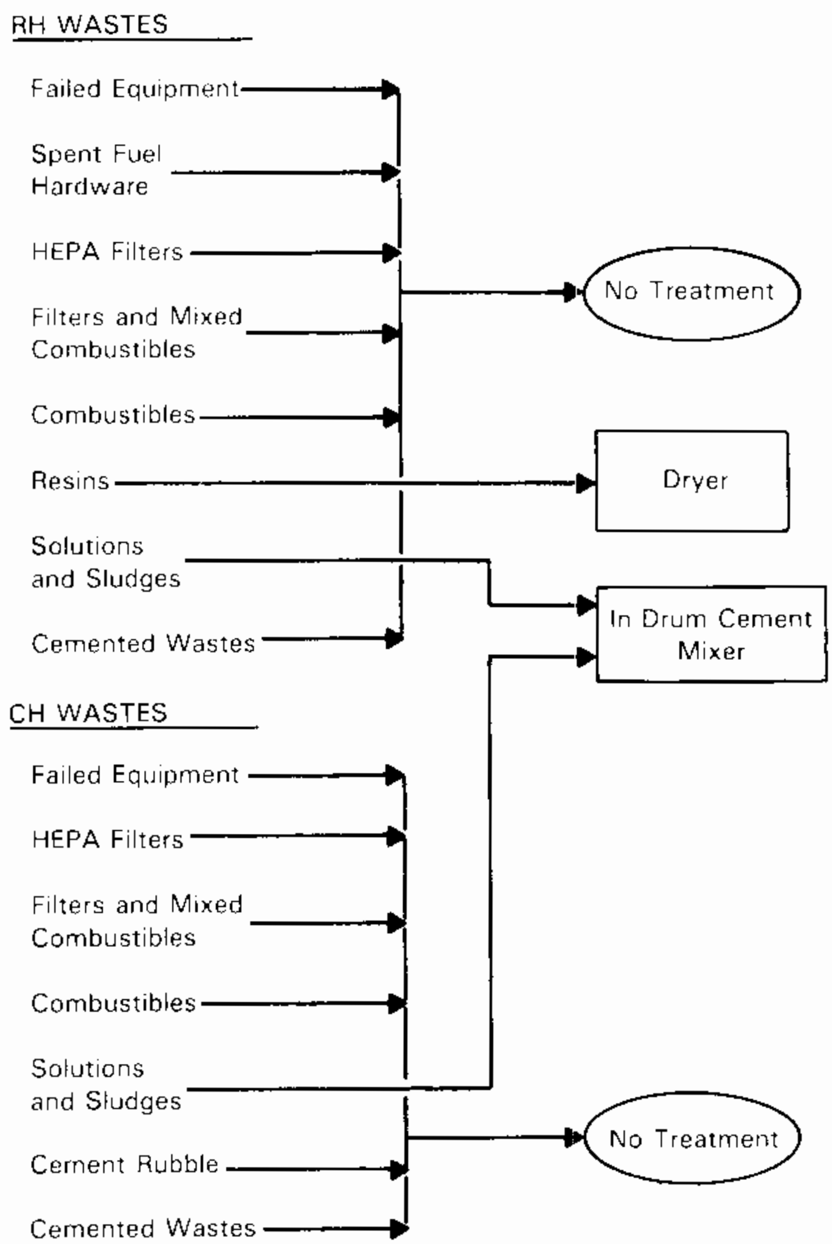


FIGURE 6.2. Alternative 1: Process Flow Diagram with No Treatment

The major processes identified in Figure 6.3 are the separation and compaction of the HEPA filters and other mixed combustibles and filters. The combustibles, resins, solutions, and sludges are cemented in 208-L drums. Commercial cemented wastes prepared offsite are not further treated. These processes result in the waste volumes shown in Table 6.2. The major parameters selected in the calculations are: the filters are compacted by a factor of 4

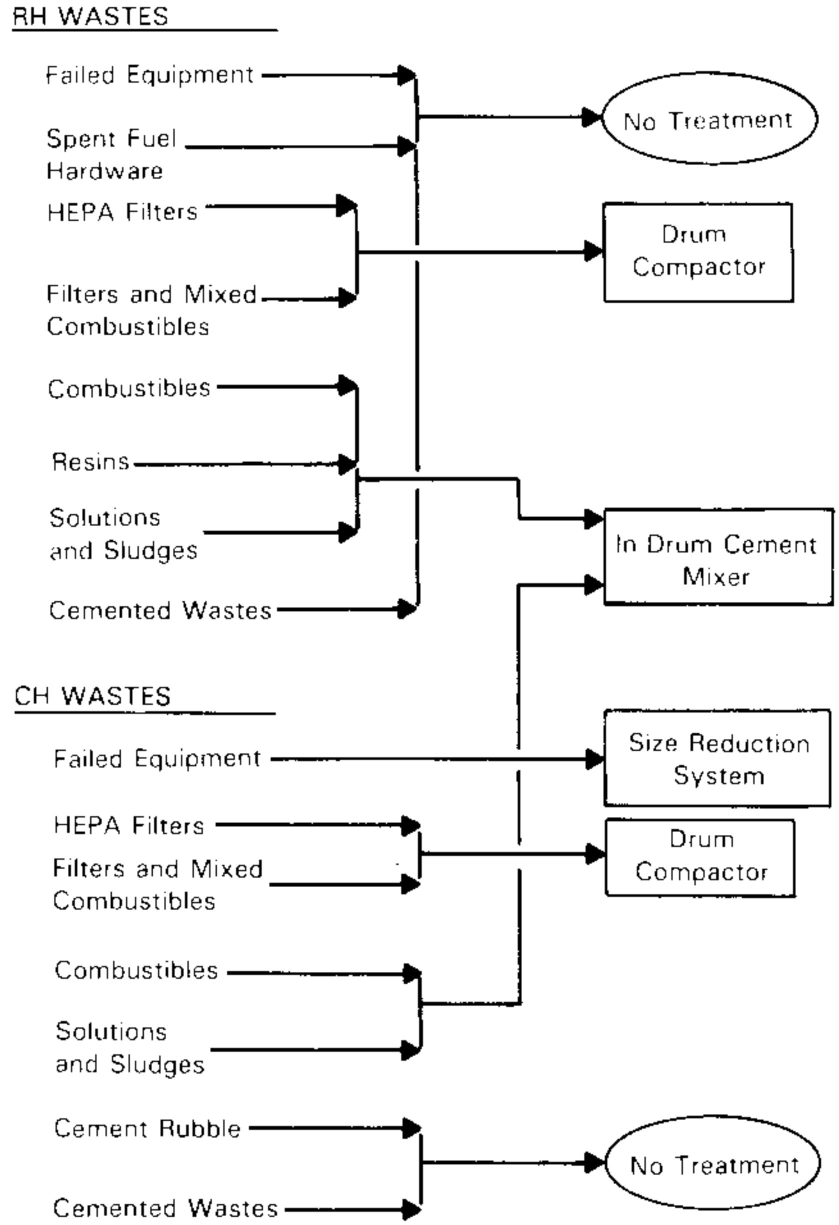


FIGURE 6.3. Alternative 2: Process Flow Diagram for the Reference MRS Facility

from their untreated volume; the combustibles are limited to 25 vol% of the package; wet resins are loaded into cement at 35 wt%; solutions and sludges are incorporated into cement at 60 wt%; and cemented waste received from other facilities remains untreated. Following this treatment, the spent fuel hardware has the largest volume and HEPA filters comprise the second largest

TABLE 6.2. Annual Treated Waste Volumes, Weight, and Number of Packages for the MRS Reference Alternative (2)

Wastes	Volume, m^3 Untreated	Volume, m^3 Treated	Weight, kg Untreated	Weight, kg Treated	Density, kg/m^3 Untreated	Density, kg/m^3 Treated	Number of Packages 208L
RH Wastes							
Failed Equipment	27	18	8,640	28,800	320	480	87
Spent Fuel Hardware	450	450	405,000	405,000	900	900	2,163
HEPA Filters	786	196	126,000	126,000	160	640	944
Filters and Mixed Combustibles	66	28	19,800	19,800	300	720	132
Combustibles	5	3	1,135	4,540	250	1,600	15
Resins	2	3	2,000	4,167	1,000	1,600	14
Solutions and Sludges	3	3	2,800	4,667	1,100	1,600	16
Cemented Wastes	59	59	94,400	94,400	1,600	1,600	284
Totals	1,400	760	659,000	687,000			3,655
CH Wastes							
Failed Equipment	116	77	37,100	37,100	320	480	372
HEPA Filters	19	5	3,100	3,100	160	640	23
Filters and Mixed Combustibles	71	30	21,300	21,300	300	720	142
Combustibles	52	36	12,900	51,700	250	1,600	173
Solutions and Sludges	2	3	2,200	3,670	1,100	1,600	12
Concrete Rubble	39	39	49,300	49,300	1,270	1,270	188
Cemented Wastes	72	72	115,000	115,000	1,600	1,600	346
Totals	371	261	241,000	281,000			1,256

Note: Data and values rounded to three significant figures, which are maintained for the calculations, but exceed the accuracy of the data.

volume. Compared to Alternative 1 total volumes have been reduced by a factor of 2 for the RH wastes and by a factor of nearly 2 for the CH wastes.

6.3 ALTERNATIVE 3--SUPERCOMPACTION

Supercompaction, a process that compresses materials at very high pressures, ~70 MPa (~10,000 psi) (Hollo and White 1985, and Sathrum and Stember 1985), provides high volume reduction of a wide variety of wastes without high process temperatures. Current experience indicates that nearly all materials can be volume-reduced with supercompaction. The supercompaction of materials somewhat confines and significantly consolidates the waste, and provides some limited improvement in waste form quality. Volume reduction factors with supercompaction are much higher than normal compaction; this decreases the disposal and transportation cost, but may increase the treatment cost.

Figure 6.4 is the process flow diagram for the supercompaction alternative. All of the wastes are treated by supercompaction except the as-received cemented wastes, which remain untreated. The supercompactor is assumed here to handle only a 208-L drum. The drum integrity is lost during the compaction process, so each of the compressed waste packages is restacked into the standard 1,280-L containers. It is expected that some of the wastes will require size reduction or precompaction to be compatible with the supercompactor.

It will also be necessary to dry the solutions and sludges before compacting them. Because of the small volume of these materials, it was assumed possible to simply dry the materials directly in a heated drum, since only 10 to 15 drums/yr will be generated.

Table 6.3 lists the final waste volumes after treatments. The treated density data for the various wastes were taken from vendor literature and the vendors' past experience with a supercompactor for selected waste types. The weight of the wastes is unchanged during the process except for the wastes that are dried. The RH and CH waste volumes are further reduced below the MRS Reference, by a factor of about 3 and by a factor of about 2, respectively.

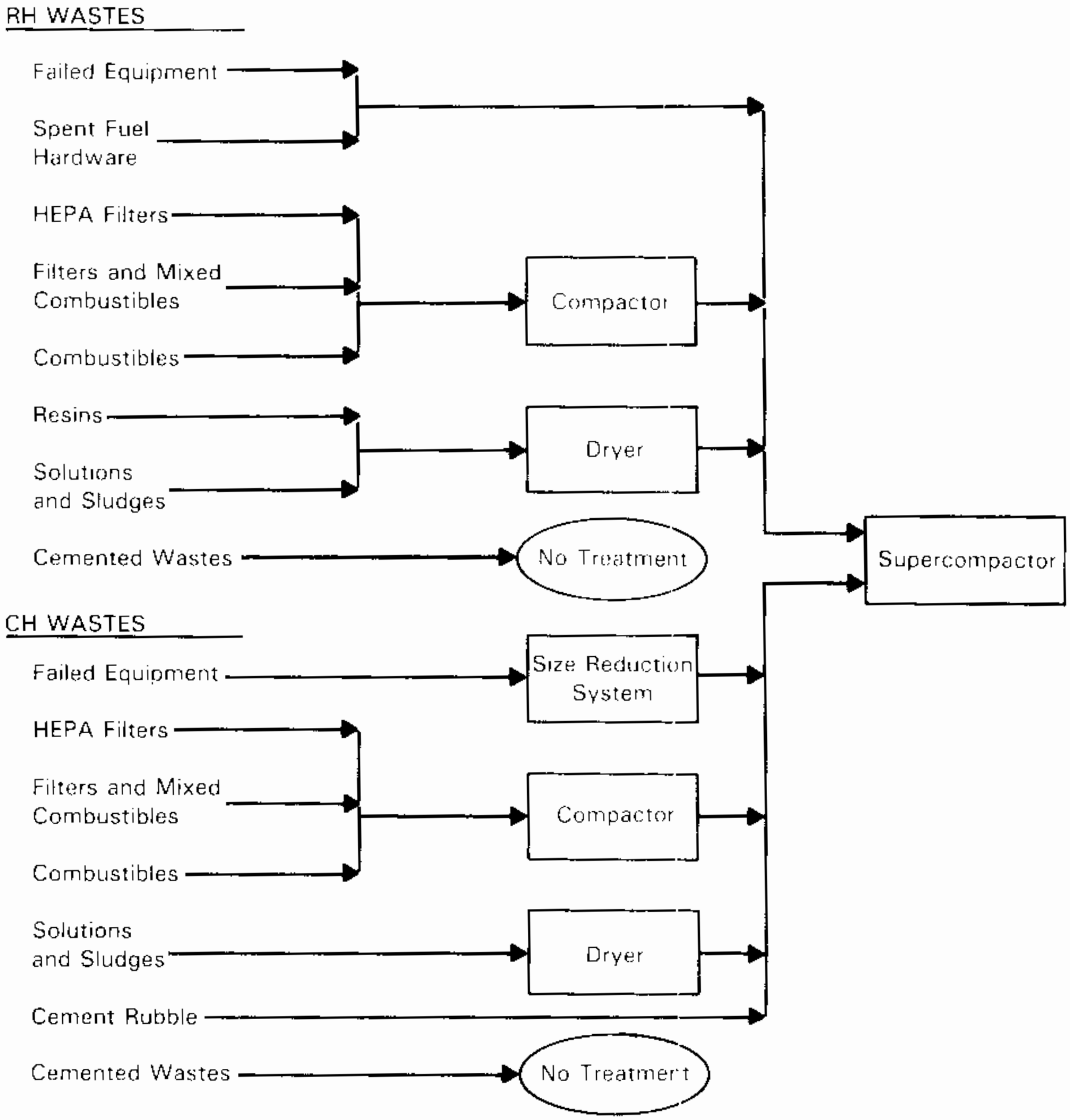


FIGURE 6.4. Alternative 3: Process Flow Diagram for Supercompaction

6.4 ALTERNATIVE 4--MVR WITH DECONTAMINATION

This processing alternative minimizes the mass and volume of the final waste form. The mass and volume reduction processes are shown in Figure 6.5. Mass reduction is achieved by two major processes. The mass of the combustibles and resins is reduced by incineration, and the mass of the surface-contaminated materials is reduced to LLW by decontamination. The incineration

TABLE 6.3. Annual Treated Waste Volumes, Weights, and Number of Packages for the Supercompaction Alternative (3)

Wastes	Volume, m³ Untreated	Volume, m³ Treated	Weight, kg Untreated	Weight, kg Treated	Density, kg/m³ Untreated	Density, kg/m³ Treated	Number of Packages 208L	Number of Packages 1280L
RH Wastes								
Failed Equipment	27	2	8,640	8,640	320	4,500		2
Spent Fuel Hardware	450	109	405,000	405,000	900	3,720		85
HEPA Filters	786	41	126,000	126,000	160	3,060		32
Filters and Mixed Combustibles	66	12	19,800	19,800	300	1,720		9
Combustibles	5	1	1,140	1,140	250	1,170		1
Resins	2	0	2,000	400	600	1,170		0
Solutions and Sludges	3	0	2,800	700	1,100	1,830		0
Cemented Wastes	59	59	94,400	94,400	1,600	1,600	284	
Totals	1,397	224	659,000	656,000			284	129
CH Wastes								
Failed Equipment	116	8	37,100	37,100	320	4,500		6
HEPA Filters	19	3	3,100	3,100	160	1,180		2
Filters and Mixed Combustibles	71	12	21,300	21,300	300	1,720		10
Combustibles	52	11	12,920	12,900	250	1,175		9
Solutions and Sludges	2	0	2,200	550	1,100	1,830		0
Concrete Rubble	39	26	49,300	49,300	1,270	1,910		20
Cemented Wastes	72	72	115,200	115,200	1,600	1,600	346	
Totals	371	132	241,000	240,000			346	47

Note: Data and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

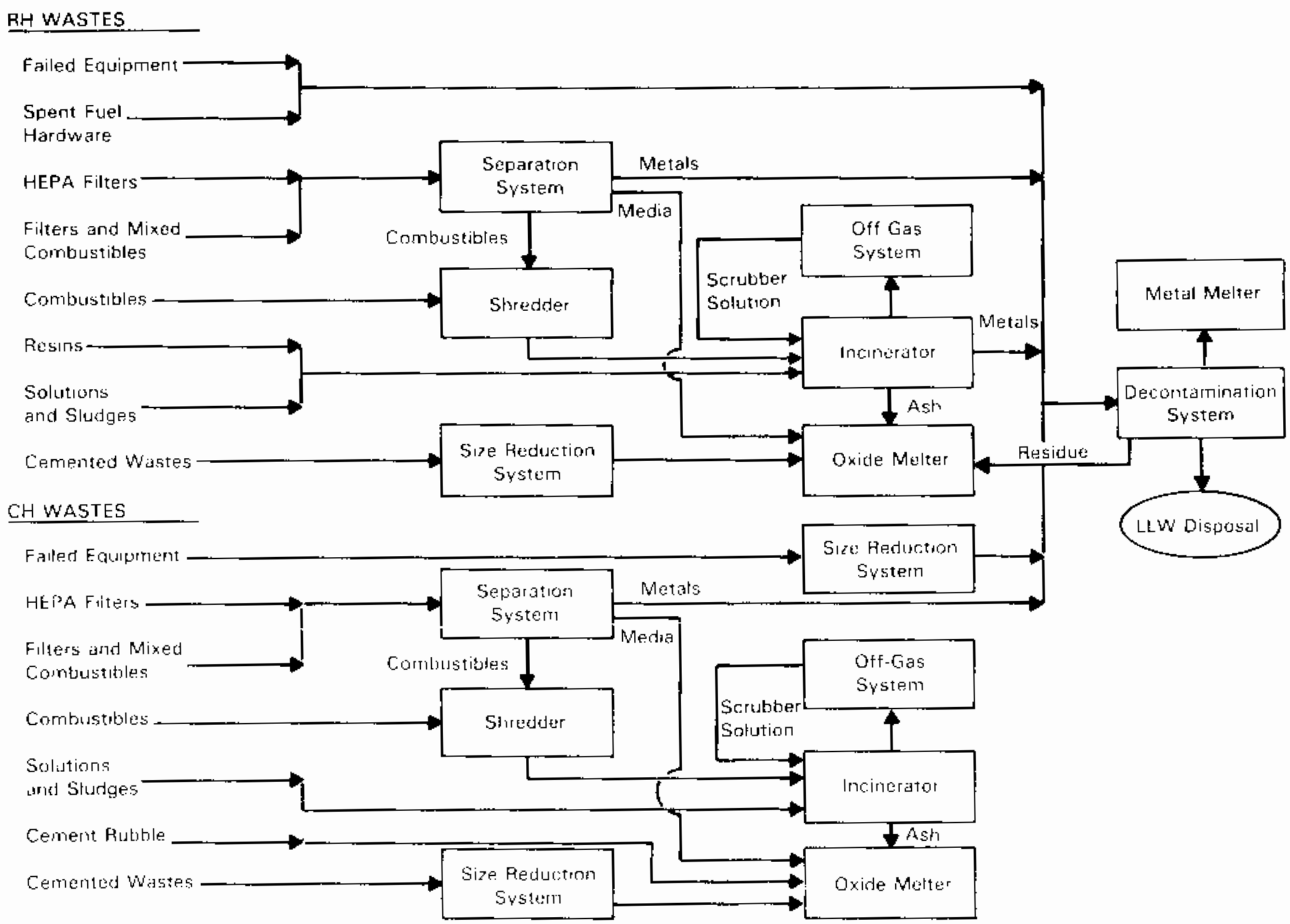


FIGURE 6.5. Alternative 4: Process Flow Diagram for MVR with Decontamination

and decontamination processes produce secondary waste streams (scrubber solution and decontamination residues) that must be concentrated and treated.

Before the wastes can be incinerated, they must be shredded to an appropriate size, and, before they can be shredded, they should have the major contaminants on them fixed to avoid generating large amounts of contaminated dust in the process cell. Decontamination converts wastes from the TRUW category to the LLW category and reduces the mass of material that must be transported to and disposed of in a deep geologic repository. The decontaminated materials would be shipped to a LLW burial ground. Decontamination is not applied to activated materials such as spent fuel hardware because their intermolecular radioactivity cannot be removed. LLW disposal costs for the HAW may well be comparable to or exceed the costs of repository disposal (Ross et al. 1985), which eliminates the cost incentive for decontamination of activated materials.

Volume reduction methods, which melt the wastes into near-theoretical density, are used to maximize volume reduction where mass cannot be reduced. As shown in Figure 6.5, three melters are needed. Two oxide melters are used, one each for CH wastes and RH wastes. However, with the periodic replacement of melting crucibles required for metal melters, it was considered possible to melt the CH wastes in the RH melter after a crucible change-out without contaminating them to the point that they become RH wastes. This alternative requires careful separation of the metals, organics or combustibles, and other materials. The metals are also separated into materials that can and cannot be decontaminated.

Table 6.4 lists waste volumes that result from this alternative. In the table, the metals are pre-sorted into those that can be decontaminated and those that cannot, and these are accounted for separately. Where incineration processes are considered, the secondary waste stream of scrubber solids is also shown, and it is postulated that the scrubber solids will be concentrated and re-fed into the incinerator. The major assumptions used in the calculations are:

- Metal is melted to 100% of theoretical density but occupies only 90 vol% in the 333-L waste containers (0.30-m-dia by 4.6-m-long).

TABLE 6.4. Annual Treated Waste Volumes, Weights, and Number of Packages for the MVR with Decontamination Alternative (4)

Wastes	Volume, m^3 Untreated	Volume, m^3 Treated	Weight, kg Untreated	Weight, kg Treated	Density, kg/m^3 Untreated	Density, kg/m^3 Treated	Number of Packages 208L	Number of Packages 303L
RH Wastes								
Failed Equipment	22		8,640		320			
Decontaminatable Metal		7		6,050		1,000	32	
Non-decontaminatable Metal		0		2,590		7,800		1
Decontamination Residue		0		50		2,300		0
Spent Fuel Hardware	450	69.20	405,000	405,000	900	6,500		208
HEPA Filters	786				160			
non-decontaminatable metal		3	22,200	22,200		7,800		8
decontaminatable metal		47	51,900	51,900		1,000	225	
combustibles		2	17,600	3,830		2,300		5
decontamination and scrubber residue		0		863		2,300		1
media		13	33,900	33,900		2,300		40
Filters and Mixed Combustibles	66				300			
non-decontaminatable metal		0	3,960	1,190		7,800		0
decontaminatable metal		2	2,770	2,770		1,000	12	
combustibles		0	14,900	743		2,300		1
decontamination and scrubber residue		0		280		2,300		0
noncombustibles		0	990	993		2,300		1
Combustibles	5	0	1,135	57	250	2,300		0
scrubber residues		0		20		2,300		0
Resins	2	0	2,000	40	1,000	2,300		0
scrubber residue		0		7		2,300		0
Solutions and Sludges	3	0	2,800	700	1,100	2,300		1
Cemented Wastes	59	30	94,400	75,500	1,600	2,300		89
Totals	1,397	174	659,475	609,000			269	355
CH Wastes								
Failed Equipment	116		37,100		320			
Decontaminatable Metal		29		26,000		1,000	139	
Non-decontaminatable Metal		1		11,100		7,800		4
Decontamination Residue		0		214		2,300		0
HEPA Filters	19				160			
non-decontaminatable metal		0	42	42		7,800		0
decontaminatable metal		0	109	109		1,000	0	
combustibles		0	1,780	89		2,300		0
decontamination and scrubber residue		0		36		2,300		0
media		0	1,160	1,160		2,300		1
Filters and Mixed Combustibles	71				300			
non-decontaminatable metal		0	4,260	1,280		7,800		0
decontaminatable metal		3	2,980	3,000		1,000	13	
combustibles		0	16,000	799		2,300		1
decontamination and scrubber residue		0		301		2,300		0
noncombustibles		0	1,070	1,070		2,300		1
Combustibles	52	0	12,900	646	250	2,300		1
scrubber residues		0		224		2,300		0
Solutions and Sludges	2	0	2,200	550	1,100	2,300		1
Concrete Rubble	39	15	49,300	39,500	1,270	2,300		46
Cemented Wastes	72	36	115,000	92,200	1,600	2,300		108
Totals	371	89	241,000	178,000			152	166

Note: Data and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

- For decontamination, 70% of the nonactivated metallic waste is postulated to be decontaminated using wet vibratory finishing. During decontamination a residue is generated from the removed surface materials and from chemicals used in the decontamination solutions. These solids are considered oxide-meltable to full density.

- The HEPA filters are separated into metals, organics, and media for specific treatments, with the media being melted to full density.

- The incineration process reduces the mass of the combustibles by 95% and the resins by 90%.[a]

- Solutions and sludges are considered to be 25 wt% solids when melted.

- Concrete and cemented wastes can be reduced by 20% in weight by melting.

- The density of melted non-metal products is that of typical glass, 2,300 kg/m^3.

- Residues from incineration and decontamination are melted to full density.

Table 6.4 shows that the volumes of waste for repository disposal are again lower than for Alternative 3 (Table 6.3) by a factor of over 2 for the RH wastes and a factor of nearly 3 for the CH wastes, when not considering the LLW volumes. Even though only a small fraction of the waste weight is reduced by the incineration and decontamination processes, the volume reductions are very significant.

No additional treatments beyond volume reduction were done to improve the chemical durability of the waste form in this alternative.

After the evaluation of the eight major alternatives described in this section, three variations were identified to optimize Alternative 4 to reduce

(a) If the wastes contain a large portion of PVC, this could result in a large secondary waste volume from the incinerator scrubber, which captures chloride ion. For our calculations we did not consider a high percentage of PVC to be present.

its processing complexity while not markedly increasing the final waste volumes or reducing the waste form quality. The three variations include:

- no processing of the cement wastes shipped to the central treatment facility from other commercial TRUW generators.
- use of decontamination.
- cementing of the residues and oxide wastes (rather than melting them).

These three variations were combined to yield four subalternatives of Alternative 4: MVR with decontamination and melting, MVR with melting only, MVR with decontamination and cementing, and MVR with cementing only.

6.4.1 Alternative 4A--MVR With Decontamination and Melting

The processing scheme for this alternative is identical to Alternative 4 except that the wastes cemented outside the central treatment facility are not retreated, and the low-volume residues and other oxide wastes are treated with the similar RH wastes to eliminate several process units. This alternative was selected to reduce the processing complexity of Alternative 4 and to allow for comparison with other modifications discussed in Sectons 6.4.2 to 6.4.4. Separate flowsheets and waste volume calculations have been omitted to simplify this report. Table 6.5 summarizes the waste volumes for Alternatives 4A, 4B, 4C, and 4D. The volumes and weights of these subalternatives are somewhat higher than those of Alternative 4. This results from not treating the cemented wastes.

6.4.2 Alternative 4B--MVR With Melting Only

This alternative is very similar to Alternatives 4 and 4A. The main difference between it and 4A is that in it no wastes are decontaminated. All metallic wastes are melted. This results in some increased mass and volume of melted metallic wastes. However, it eliminates an additional process. As in Alternative 4A, the combination of the small volumes of CH wastes with the RH wastes reduces the volume of CH wastes, and the number of process units. The final calculated waste volumes are also summarized in Table 6.5.

TABLE 6.5. Summary of Annual Treated Waste Volumes, Weights, and Number of Packages for Alternatives 4A, 4B, 4C, and 4D

Alternative	RH Wastes				CH Wastes				
	Treated Weight kg	Treated[(a)] Volume m^3	Packages of 208-L #	Packages of 333-L #	Treated[(a)] Weight kg	Treated[(a)] Volume m^3	Packages of 208-L #	Packages of 333-L #	LLW 208-L #
4	548,000	118	-	355	149,000	56	-	166	421
4A	572,000	150	284	272	177,000	113	534	5	421
4B	632,000	156	284	292	206,000	116	534	16	--
4C	683,000	220	712	217	177,000	113	534	5	421
4D	739,000	224	696	238	206,000	116	534	16	--

(a) The LLW volumes and weights are not included in the totals.

6.4.3 Alternative 4C--MVR With Decontamination and Cementing

The volume of oxides is rather small in Alternatives 4, 4A, and 4B, and process complexity is high for melting oxides and residues. Therefore, this alternative includes the cementation, rather than melting, of residues and oxides. This alternative also includes decontamination of nonactivated metals. Cementing increases the treated waste volume from Alternative 4A, but simplifies the processing.

6.4.4 Alternative 4D--MVR With Cementing Only

This is the simplest of the four optimized subalternatives of Alternative 4. It combines the cementing of Alternative 4C with the elimination of the decontamination of Alternative 4B. In this alternative, previously cemented wastes are not treated; all the wastes are processed in one remote shredder and incinerator. All the metals are melted and the oxides and residues are cemented. This alternative has the largest waste volume of these four modifications to Alternative 4.

The waste volumes, weights, and number of canisters for the alternatives are summarized in Table 6.5.

6.5 ALTERNATIVE 5--CEMENTATION

Cementation is currently applied to a wide variety of wastes, including many TRUW. It was recommended for consideration for some types of commercial TRUW in a previous assessment (Ross et al. 1985) and is planned for treatment of defense TRUW to prepare them for WIPP. All wastes can be treated at ambient temperature by cementation without the need for additional processes, thus keeping the treatment costs low because only one simple process is needed. Cementation provides a degree of waste confinement and renders combustible materials essentially noncombustible. However, cementation does not provide major volume reduction and increases the mass of material that must be transported to and placed in a repository. Cemented waste forms also have the potential to generate radiolytic gas.

Cementing or grouting will provide containment for the wastes in a nearly uniform matrix. The process flow diagram for cementation (Figure 6.6) shows a

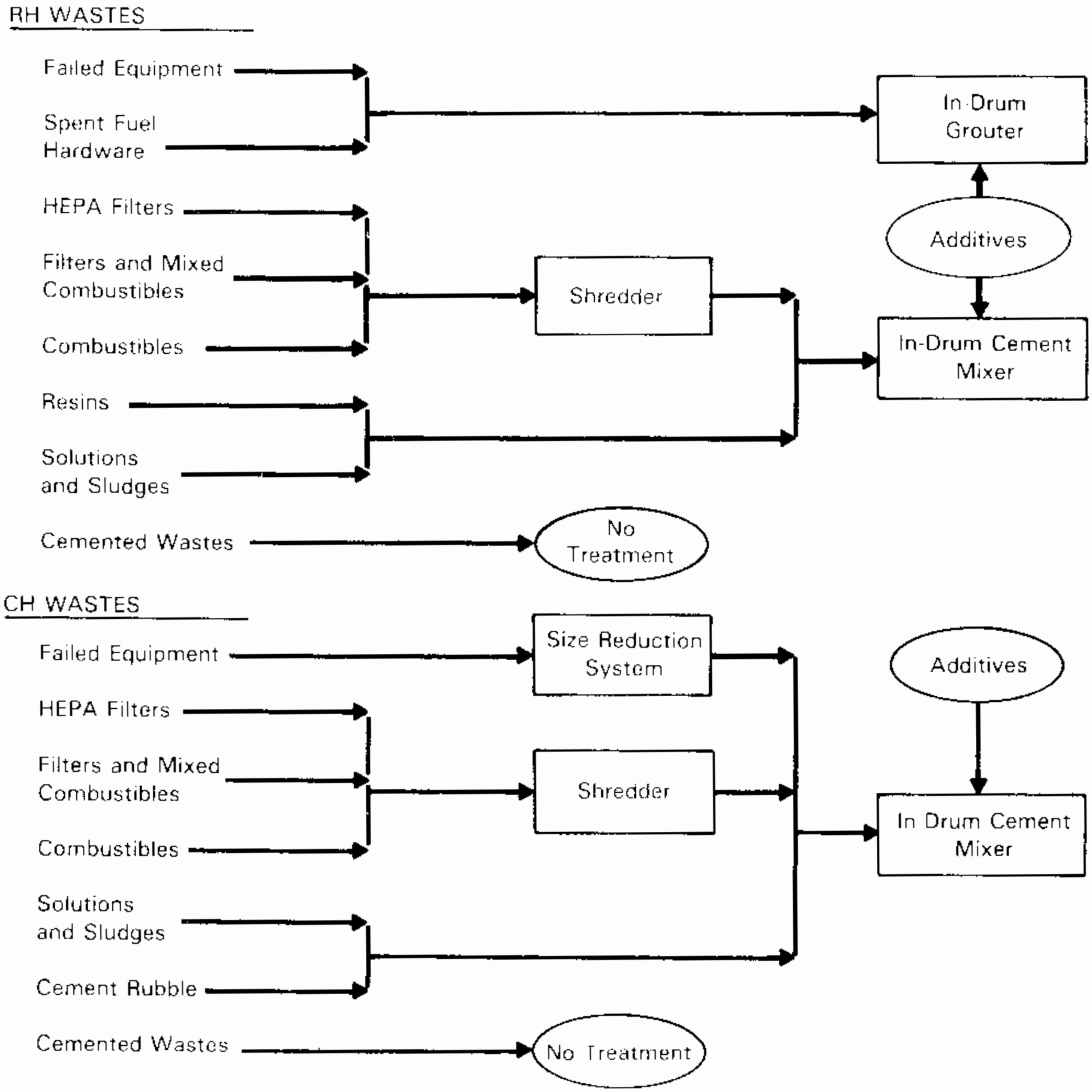


FIGURE 6.6. Alternative 5: Process Flow Diagram for Cementation

minimum number of process steps. All processes are at room temperature, and no volatiles are formed. The wastes are reduced in size to fit inside 208-L drums. Three different size-reduction or shredding operations are needed. The first is a size-reduction operation for CH failed equipment, and the second and third are shredders (one CH and one RH) for HEPA filters, combustibles, and other mixed wastes. As with the previous alternatives, a process to fix activity on HEPA filters before shredding them is included. The large bulky wastes such as spent fuel hardware and failed equipment, which are loaded into a drum during processing, are grouted with cement. Other wastes such as the shredded materials, resins, solutions, and sludges are added to the drum and mixed with the cement by an in-drum process.

The resulting volumes of waste are shown in Table 6.6. It can be noted that the waste volumes are reduced from Alternative 1, principally by the reduced volume of HEPA filters. Note that the weight of the processed wastes is about double that of the other alternatives. The major assumptions used in these calculations were: a 30 wt% loading of shredded materials into the cement, a maximum 25 wt% loading of combustible materials into the cement, a 35 wt% loading of resins into the cement, and a 60 wt% loading of solution and sludges into the cement. A final cement density of 1,600 kg/m^3 was used to calculate the final weight of the solidified wastes (except where materials are grouted and the weight of the waste significantly increases the bulk density).

6.6 ALTERNATIVE 6--ARC PYROLYSIS AND MELTING

Arc pyrolysis and melting is a potential new concept for TRUW treatment. In an arc pyrolysis melter all wastes can be treated. The organic and combustible materials are pyrolyzed and removed from the furnace for additional treatment. The residual metals and oxides are melted into slag and molten metal layers. Periodically the melted materials are removed from the furnace and cast into canisters. A unit has been recently designed and proposed for the destruction of capacitors containing polychlorinated biphenyls (PCBs) (Wittele, Titus and Boice 1984). Its application to radioactive waste has not been previously demonstrated, so selection of this technology will require feasibility testing and process demonstration activities.

The bulk waste could be fed to the arc pyrolysis melter to produce a waste form similar to that produced by Alternative 4. Figure 6.7 shows that all of the wastes are fed to the arc pyrolysis melter with only limited pretreatment. This requires the arc furnace to have a large internal capacity for

TABLE 6.6. Annual Treated Waste Volumes, Weights, and Number of Packages for the Cementation Alternative (5)

Wastes	Volume, m^3		Weight, kg		Density, kg/m^3		Number of Packages
	Untreated	Treated	Untreated	Treated	Untreated	Treated	208L
RH Wastes							
Failed Equipment	27	27	8,640	43,200	320	1,600	130
Spent Fuel Hardware	450	450	405,000	720,000	900	1,600	216
HEPA Filters	786	291	125,700	419,000	160	1,600	1,400
Filters and Mixed Combustibles	66	46	19,800	66,000	300	1,600	220
Combustibles	5	3	1,135	4,540	250	1,600	15
Resins	2	4	2,000	5,714	1,000	1,600	19
Solutions and Sludges	3	3	2,800	4,607	1,100	1,600	16
Cemented Wastes	59	59	94,400	94,400	1,600	1,600	284
Totals	1,400	883	659,000	1,360,000			4,250
CH Wastes							
Failed Equipment	116	116	37,100	186,000	320	1,600	558
HEPA Filters	19	7	3,100	10,300	160	1,600	34
Filters and Mixed Combustibles	71	49	21,300	71,000	300	1,600	237
Combustibles	52	36	12,900	51,700	250	1,600	173
Solutions and Sludges	2	3	2,200	3,670	1,100	1,600	12
Concrete Rubble	39	39	49,300	49,300	1,270	1,270	188
Cemented Wastes	72	72	115,000	115,000	1,600	1,600	346
Totals	371	322	241,000	487,000			1,550

Note: Data and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

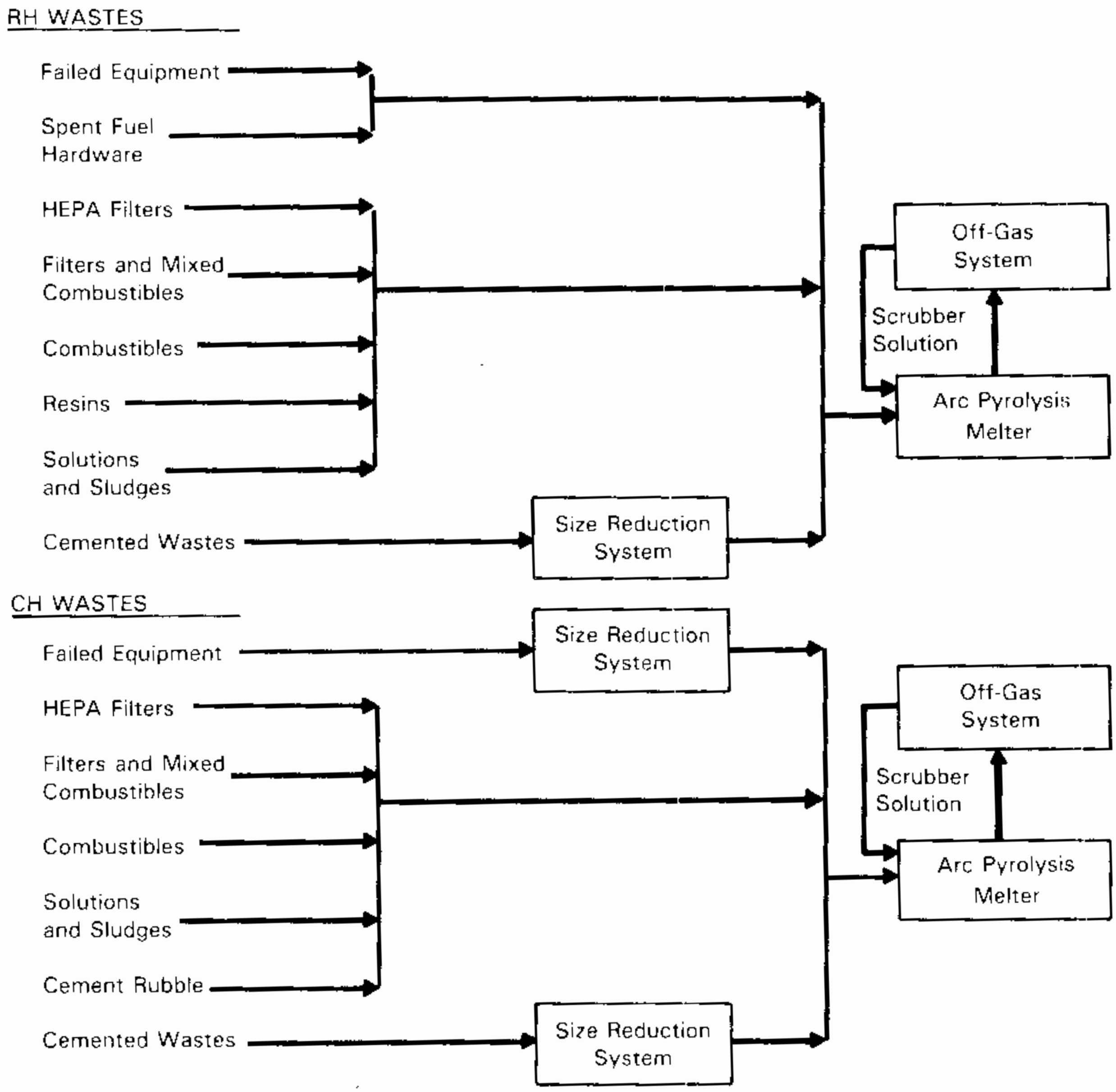


FIGURE 6.7. Alternative 6: Process Flow Diagram for Arc Pyrolysis and Melting

charging of HEPA filters and other bulky wastes. Combustibles would be pyrolyzed and eliminated and the metals and oxides would be melted and cast directly into the 333-L drums.

The resulting waste volumes and masses are shown in Table 6.7. The volumes are small and the masses have been reduced but will exceed those of

TABLE 6.7. Annual Treated Waste Volumes, Weights, and Number of Packages for the Arc Pyrolysis and Melting Alternative (6)

Wastes	Volume, m³		Weight, kg		Density, kg/m³		Number of Packages
	Untreated	Treated	Untreated	Treated	Untreated	Treated	333L
RH Wastes							
Failed Equipment	27	1	8,640	8,640	320	7,800	4
Spent Fuel Hardware	450	69	405,000	405,000	900	6,500	208
HEPA Filters	786	22	126,000	113,000	160	5,800	65
Filters and Mixed Combustibles	66	1	19,800	4,750	300	5,740	3
Combustibles	5	0	1,135	57	250	2,300	0
Resins	2	0	2,000	80	1,000	2,300	0
Solutions and Sludges	3	0	2,800	700	1,100	2,300	1
Cemented Wastes	59	36	94,400	75,500	1,600	2,300	110
Totals	1,400	130	659,000	608,000			390
CH Wastes							
Failed Equipment	116	5	37,100	37,100	320	7,800	16
HEPA Filters	19	1	3,100	1,580	160	2,730	2
Filters and Mixed Combustibles	71	1	21,300	5,110	300	5,740	3
Combustibles	52	0	12,900	646	250	2,300	1
Solutions and Sludges	2	0	2,200	550	1,100	2,300	1
Concrete Rubble	39	19	49,300	39,500	1,270	2,300	57
Cemented Wastes	72	45	115,000	92,200	1,600	2,300	134
Totals	371	71	241,000	177,000			213

Note: Oata and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

Alternative 4 because no metallics are removed from the process by decontamination. In calculating the final waste quantities, it was assumed that the metals are near theoretical density, that the melted density of the HEPA filters is a composite of the metals and the oxides, that melted oxides would have a density similar to that of glass, and that cements have 20% water, which will be released through the off-gas treatment system. The remaining fraction of ash is the same as for the incineration processes. Potential increases in mass from additives in the off-gas system have not been included but are expected to be less than 2% of the totals. As arc pyrolysis and melting becomes better understood, it is expected that waste treatment processing problems will be identified.

6.7 ALTERNATIVE 7--SULFUR-BONDED GRAPHITE WASTE FORM

The previous alternatives have been primarily concerned with processing ease and volume reduction. This waste treatment alternative is concerned with producing a combination of waste forms that each have potentially good chemical durability. To achieve this the recently conceived process of incorporating the wastes into a sulfur-bonded graphite at a low temperature is used. Graphite has the highest chemical durability of any material tested to date, but is normally difficult to process. The wastes are incorporated into flake graphite at low temperature by adding a small fraction of sulfur to the graphite powder. The total mixture is pressed at moderate pressure and low temperature. The sulfur melts at a relatively low temperature and, under moderate pressure, fills the voids in natural flake graphite. Sulfur is very insoluble in oxygen-free water and thus will resist reaction with the low-oxygen-content groundwater expected at typical basalt repository depths.

The process flow diagram for this alternative is shown in Figure 6.8. Metallic wastes are separated from the organic and oxide wastes and melted separately as in several of the previous alternatives. The combustibles are incinerated, and the ash and other oxides are ground and mixed intimately with natural flake graphite and about 8 wt% sulfur, which is then pressed in a die or container at a pressure of about 34 MPa (5,000 psi) to form billets measuring about 0.30-m dia by 0.30-m high. The billets are heated to a low

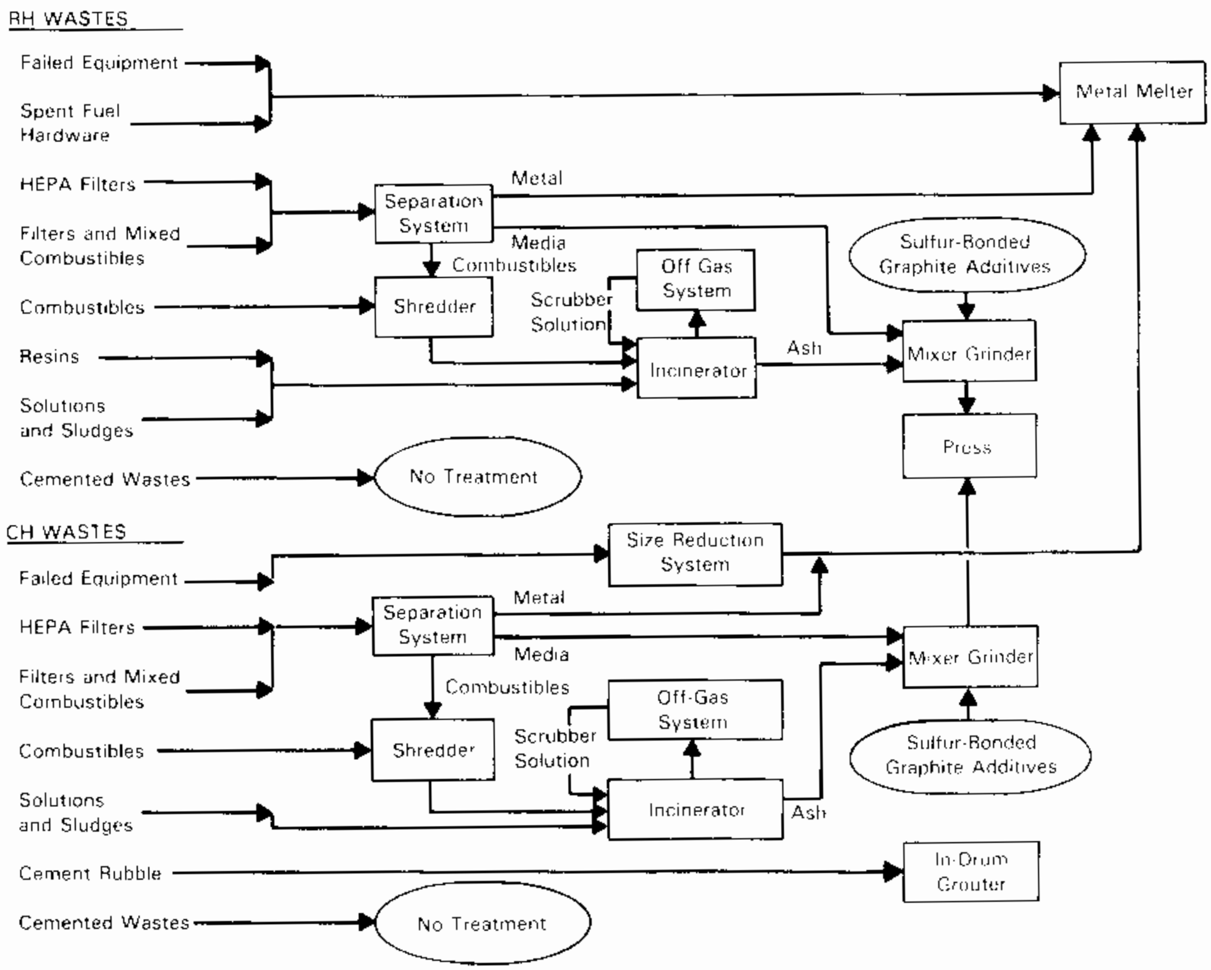


FIGURE 6.8. Alternative 7: Process Flow Diagram for the Sulfur-Bonded Graphite Waste Form

temperature (~150°C) before or during the pressing to melt the sulfur, which fills the porosity of the flake graphite during pressing. The final billets are then loaded into a ~0.30-m-dia by 4.6-m-long canister.

Melting the metallic wastes reduces the metallic waste streams to a small volume as in Alternatives 4 and 6. The other materials are loaded into the sulfur-bonded graphite at a 30 wt% loading. The addition of the graphite and sulfur to the waste results in an overall increase in weight, but the ensuing processing reduces the volume. Table 6.8 lists density and volume information. Because graphite and sulfur will oxidize, this waste form is considered to be of intermediate quality.

TABLE 6.8. Annual Treated Waste Volumes, Weights, and Number of Packages for the Sulfur-Bonded Graphite Alternative (7)

Wastes	Volume, m^3 Untreated	Volume, m^3 Treated	Weight, kg Untreated	Weight, kg Treated	Density, kg/m^3 Untreated	Density, kg/m^3 Treated	Number of Packages 208L	Number of Packages 333L	Number of Packages 1280L
RH Wastes									
Failed Equipment	27	1	8,640	8,640	320	7,800		4	
Spent Fuel Hardware	450	69	405,000	405,000	900	6,500		208	
HEPA Filters	786				160				
metals		11	74,200	74,200		7,800		32	
combustibles		8	17,600	15,300		2,200			6
media		57	33,400	113,000		2,200			45
Filters and Mixed Combustibles	66				300				
metals		1	3,960	3,960		7,800		2	
combustibles		1	14,900	2,480		2,200			1
noncombustibles		2	990	3,300		2,200			1
Combustibles	5	0	1,135	189	250	2,300			1
Resins	2	1	2,000	1,330	1,000	2,300			1
Solutions and Sludges	3	1	2,800	2,330	1,100	2,300			1
Cemented Wastes	59	59	94,400	94,400	1,600	1,600	284		
Totals	1,400	237	705,000	724,000			284	245	54
CH Wastes									
Failed Equipment	116	5	37,120	37,100	320	7,800		16	
HEPA Filters	19				160				
metals		0	155	155	160	7,800		0	
combustibles		0	1,780	374		2,200			0
media		2	1,160	3,875		2,200			2
Filter and Mixed Combustibles	71				300				
metals		1	4,260	4,260		7,800		2	
combustibles		1	16,000	2,660		2,200			1
noncombustibles		2	1,070	3,550		2,200			1
Combustibles	52	1	12,900	2,153	250	2,200			1
Solutions and Sludges	2	1	2,200	1,833	1,100	2,200			1
Concrete Rubble	39	69	49,300	98,700	1,270	1,600	329		
Cemented Wastes	72	72	115,000	115,000	1,600	1,600	346		
Totals	371	154	241,000	270,000			676	18	6

Note: Data and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

6.8 ALTERNATIVE 8--HIGHEST-QUALITY WASTE FORM

This waste treatment alternative process was designed to produce waste forms of the highest quality, that will have good chemical durability, eliminate all organics and combustibles, consolidate all the particulates, eliminate any pyrophoric tendencies, eliminate concerns about radiolytic gas generation in cements, and have high density within the waste package. All of the wastes are processed into melted metal or ceramic forms, designed to be of higher quality than the simpler melted forms of Alternative 4. This alternative uses metal melting processes similar to Alternatives 4, 6, and 7, but provides for the addition of alloying materials to further increase the chemical durability of the treated metal waste form. The oxide materials are consolidated into ceramic forms by hot pressing with 30% additives to tailor the composition and increase its chemical durability. These additions increase the mass of the final waste forms, but only slightly compared to the potential volume reduction. All of the waste forms are expected be acceptable at a repository.

Figure 6.9 is the basic process flow diagram for Alternative 8. Special features of this alternative include crushing and calcining the previously solidified cements to allow them to be incorporated into the ceramic forms. It is assumed that the cements contain 20% water, released during calcining. Ninety-five wt% of the combustibles are eliminated by incineration, and the resulting ash is also added to the ceramic forms. Four hot presses were considered necessary to process the CH and the RH wastes.

The final waste form volumes are shown in Table 6.9. The wastes are assumed to be processed to high densities of either 7,800 or 6,500 kg/m^3 for metals or 2,300 kg/m^3 for ceramics. The increase in weights and volumes over Alternatives 4 and 6 results from the addition of selected materials that can increase the chemical durability. Some waste compositions may require more than 30% additives to achieve a high-quality waste form, but others could be achieved with little or no additive. The additives and their quantity would have to be determined by additional testing. For the incinerator alternatives, the use of a scrubber is assumed, and the additives from off-gas scrubbing are calculated into the mass of material processed. The majority of the treated RH wastes are metal, but the oxide waste volumes are larger for the CH wastes.

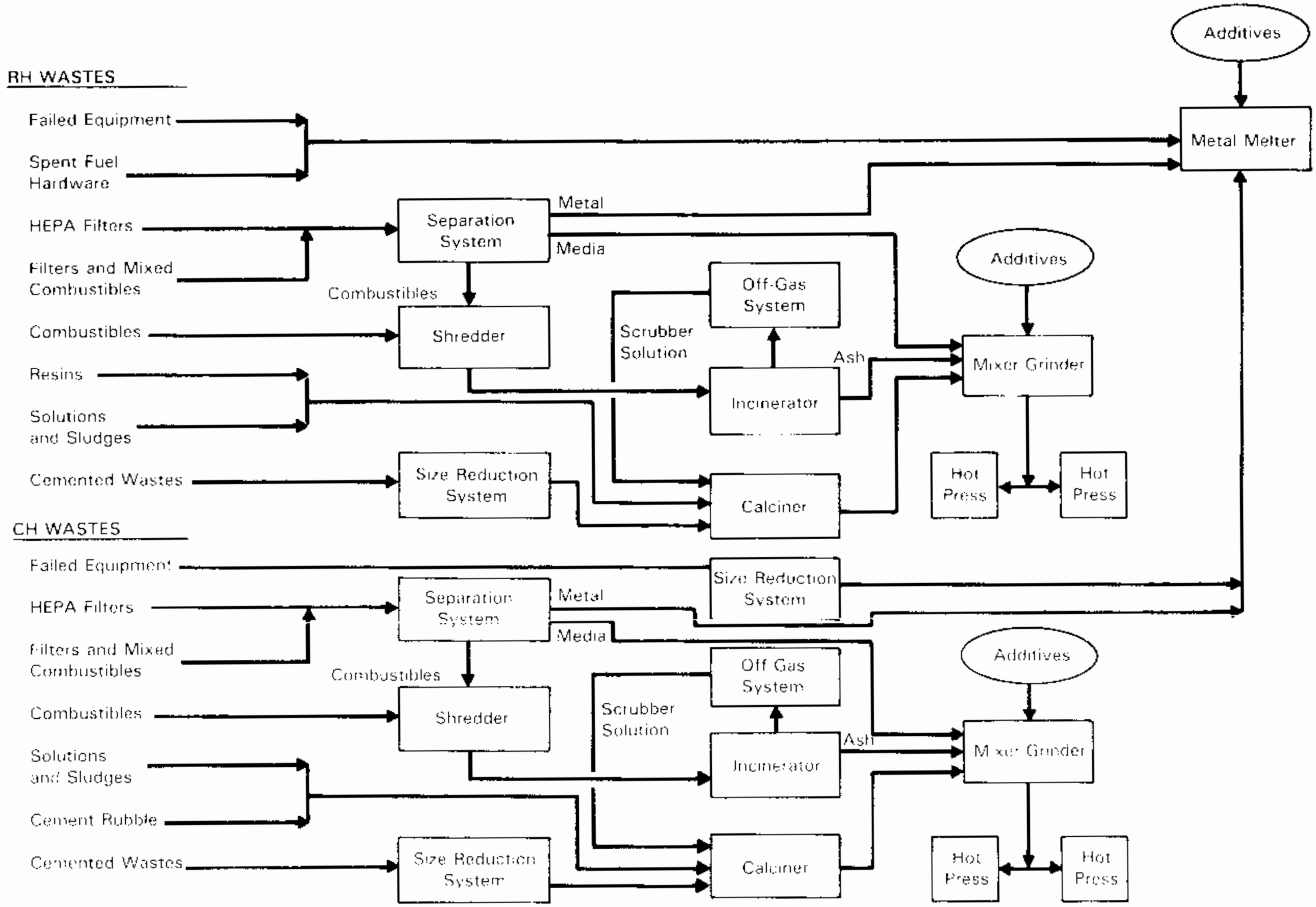


FIGURE 6.9. Alternative 8: Process Flow Diagram for the Highest-Quality Waste Form

TABLE 6.9. Annual Treated Waste Volumes, Weights, and Number of Packages for the Highest-Quality Waste Form Alternative (8)

Wastes	Volume, m^3		Weight, kg		Density, kg/m^3		Number of Packages
	Untreated	Treated	Untreated	Treated	Untreated	Treated	333L
RH Wastes							
Failed Equipment	27	1	8,640	11,200	320	7,800	4
Spent Fuel Hardware	450	90	405,000	527,000	900	6,500	270
HEPA Filters	786				160		
metals		11	126,000	96,400		2,300	33
combustibles		2	17,600	5,460		2,300	76
media		17	33,900	44,100		2,300	52
Filters and Mixed Combustibles	66				300		
metals		1	3,960	5,150		7,800	2
combustibles		1	14,900	1,330		2,300	1
noncombustibles		1	990	1,290		2,300	2
Combustibles	5	0	1,135	100	250	2,300	0
Resins	2	0	2,000	61	1,000	2,300	0
Solutions and Sludges	3	0	2,800	910	1,100	2,300	1
Cemented Wastes	59	38	94,400	98,200	1,600	2,300	115
Totals	1,400	162	659,000	791,000			487
CH Wastes							
Failed Equipment	116	4	37,100	48,300	320	1,000	11
HEPA Filters	19				160		
metals		0	155	202		7,800	0
combustibles		0	1,780	14		2,300	0
media		1	1,260	1,510		2,300	2
Filters and Mixed Combustibles	71				300		
metals		1	4,260	5,540		7,800	2
combustibles		0	16,000	1,420		2,300	1
noncombustibles		1	1,070	1,390		1,300	2
Combustibles	52	0	12,900	1,150	250	2,300	1
Solutions and Sludges	2	0	2,200	715	1,100	2,300	1
Concrete Rubble	39	20	49,300	51,300	1,270	2,300	60
Concrete Wastes	72	47	115,000	120,000	1,600	2,300	141
Totals	371	74	241,000	231,000			221

Note: Data and values rounded to three significant figures, which are maintained for the calculations but exceed the accuracy of the data.

All of the RH wastes are solidified in 0.30-m-dia by 4.6-m-long canisters with internal volumes of about 333 L. These are the same length as the proposed spent fuel containers, but smaller in diameter because of expected repository weight limits.

6.9 SUMMARY OF WASTE VOLUMES

Table 1 summarizes the waste treatment alternatives, with the specific treatment for each of the various types of waste in brief format. Table 6.10 summarizes the waste volumes, container sizes, and the number of containers for each of the alternatives. The values in this table were taken from the previous tables of this section. The final waste volumes are largest for Alternative 1 and lowest for Alternative 4, with a difference of a factor of about 20 for RH wastes and a factor of about 12 for the CH wastes. Alternative 4 has the lowest weight of TRUW, but produces a significant volume of LLW. The cementation alternative (Alternative 5) has the highest weight, but still achieves a volume reduction of a factor of about 2 over the no-treatment alternative (Alternative 1). The values in Table 6.10 are used throughout the remainder of the report to further evaluate the alternatives.

TABLE 6.10. Summary of Annual Waste Volumes, Weights and Number of Packages for Each Alternative

Alternative	RH Wastes							LLW[a]	CH Wastes					
	Treated Weight, kg	Packaged Volumes, m^3	Number of Packages in Each Size						Treated Weight, kg	Packaged Volumes, $in.^3$	Number of Packages in Each Size			
			208L	303L	333L	1,280L	3,000L	208L			208L	303L	333L	1,280L
1	708,000	2,310	2,490			82	563		257,000	584	120	681		
2	734,000	800	3,850						305,000	286	1,380			
3	700,000	239	284			140			256,000	146	346			58
4	570,000	124			374			503	155,000	57			172	
4A	679,000	154	290	297				503	188,000	113	534		5	
4B	688,000	177	284	352					207,000	117	534		18	
4C	698,000	225	730	219				503	188,000	113	534		5	
4D	775,000	240	745	256					207,000	138	631		18	
5	1,500,000	985	4,740						542,000	360	1,730			
6	648,000	138		414					184,000	74			222	
7	797,000	237	284	256	73				289,000	163	676		18	13
8	843,000	173		520					239,000	77			230	

(a) LLW volumes and weights are not included in totals.

7.0 COST CONSIDERATIONS

For each of the TRUW treatment alternatives studied, cost estimates were prepared. The cost of each of the following activities was estimated:

- Constructing and operating the TRUW and HAW treatment portions of the central treatment facility, including associated service facilities. (These costs are assumed to be incremental to those already planned for the MRS facility that is used as the reference.)
- Decommissioning the incremental facilities
- Transportation of the TRUW and HAW to the deep geologic repository and incremental LLW to a shallow land burial ground
- Disposal of the TRUW and HAW in a deep geologic repository and disposal of incremental LLW in a commercial shallow land burial ground where applicable.

The costs are in late-1985 dollars on an undiscounted basis. Costs for R&D, licensing, selection, and development of the repository were not included.

7.1 COST OF TRUW TREATMENT FACILITIES

The capital and operating costs were estimated for the TRUW treatment facilities (incremental to the main parts of the MRS facility) for each alternative studied. It was assumed that the MRS facility will process 70,000 MTU of spent fuel at the rate of 3,000 MTU/yr for 23.3 years. The MRS facility will process the internally generated TRUW (from spent fuel consolidation) and the incoming untreated TRUW from commercial facilities during those same 23.3 years.

7.1.1 Capital Costs for TRUW Treatment Facilities

The capital costs include:

- designing and constructing the incremental treatment facility and associated service areas, including the installed cost of the equipment to process the wastes

- pretreatment, which may be necessary to prepare the wastes, for the mainline treatment steps
- placing the waste in canisters
- assay and certification
- four-month interim lag storage of the treated wastes
- loadout for transportation to the disposal site.

Costs for front-end facilities common to all alternatives are not included (e.g., receiving and unloading, front-end lag storage, and gross sorting into RH, CH, and general waste types).

The capital cost estimates (Table 7.1) for this study are based on general unit factors (see Appendix B). Costs were estimated for mainline treatment equipment for the capacity of interest, with factors applied for modification for radioactive application and installation. Based on the overall size of the equipment, space requirements were estimated for the mainline equipment with allowances for access, accessory equipment, piping, wiring, controls, in-plant transport equipment, and short-term in-line lag storage. Volume-based unit factors were then used to estimate cell or process room facility and service facility costs.

The capital cost for all alternatives is modest at most, ranging from about $19 to $55 million. As expected, capital for RH processing is typically several times higher than for CH processing. The four months of lag storage and assay facilities for treated waste comprise the predominant cost element for the alternatives with little or no volume reduction (Alternatives 1, 2, and 5), but become a small fraction of the total capital costs for the alternatives with significant volume reduction (Alternatives 4, 6, 7, and 8).

7.1.2 Operating Costs for TRUW Treatment Facilities

The operating costs include all the labor, maintenance, utilities, canisters, all other materials, and occasional facility upgrading for operating the incremental TRUW treatment facility and associated service areas. These operating costs are for the incremental facilities for which the capital cost estimates were presented in the preceding subsection.

TABLE 7.1. Capital Costs for the TRUW and HAW Treatment Alternatives[a]

Cost Element	Cost by Alternative, $M											
	1	2	3	4	4A	4B	4C	4D	5	6	7	8
RH Waste	2.2	3.9	9.3	22.7	22.1	20.9	19.1	18.0	5.2	15.0	18.7	27.3
CH Waste	0.0	1.9	0.7	8.2	0.5	0.5	0.5	0.5	1.9	7.1	5.5	10.5
Stg-Assay	43.8	21.8	8.5	4.9	6.3	6.5	8.2	8.3	24.8	5.4	8.2	6.3
Total[b]	46.0	27.6	18.5	35.8	28.9	27.9	27.8	26.8	31.9	27.5	32.4	44.1

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.

(b) Total values are rounded from sum of detailed numbers given in Appendix B.

The operating cost estimates are based on fractions of the capital costs for the various process and handling steps, as developed by Ross et al. (1985). The fractions were derived from the authors' analysis of the costs in other studies (U.S. DOE 1979 and McKee et al. 1984). The fractions vary for the different process and handling steps, depending on the type of operation. Detailed tables showing the development of operating costs are in Appendix B. The estimated operating costs for each alternative are in Table 7.2. Operating costs are given on an annual basis and for the assumed facility operating life of 23.3 years.

The lifetime operating costs for all alternatives are three to four times greater than the capital costs. Canister costs are a significant part of the operating costs for all alternatives, and are the majority of the operating costs for Alternatives 1, 3, and 6. Storage/assay costs are highest for the alternatives with the highest final waste volumes (Alternatives 1 and 5).

7.1.3 Summary of TRUW Facility Costs

The life-cycle capital and operating costs and the decommissioning costs for the incremental treatment facility are summarized in Table 7.3, which shows the dominance of the operating costs in the total lifetime costs of the incremental TRUW treatment facility. Decommissioning costs, which are based on a fraction of the initial capital costs (U.S. DOE 1986), are the smallest cost element of the three major cost elements in Table 7.3.

7.2 TRANSPORTATION COSTS

The treated TRUW are assumed to be shipped by rail to a deep geologic repository that is 2,000 miles from the central treatment facility. All RH-TRUW or HAW are assumed to be shipped in 100-t casks, and CH-TRUW are assumed to be shipped in two TRUPACTs/rail car. All shipments of treated TRUW are in five-car dedicated trains. Low-level secondary wastes are assumed to be shipped by truck to a privately owned shallow land burial ground that is 300 miles away.

Shipment of the TRUW and HAW is assumed to be done with a rail transportation system, owned and operated by the federal government, using five-car

TABLE 7.2. Operating Costs for the TRUW and HAW Treatment Alternatives[a]

Cost Element	1	2	3	4	4A	4B	4C	4D	5	6	7	8
	Cost by Alternatives, $M											
Annual Costs, $M/yr												
RH-General	0.1	0.2	0.7	2.0	1.9	1.8	1.6	1.5	0.2	1.4	1.7	2.4
RH-Cans	4.5	1.2	1.2	1.7	1.4	1.4	1.3	1.3	1.4	1.8	1.7	2.3
RH-Stg-Assay	1.5	1.8	0.2	0.3	0.4	0.3	0.7	0.5	2.1	0.2	0.3	0.2
RH-Total[b]	6.1	3.3	2.1	4.0	3.7	3.5	3.6	3.2	3.8	3.4	3.6	4.9
CH-General	<0.1	0.1	0.1	0.7	0.1	0.1	0.1	0.1	0.1	0.7	0.5	6.9
CH-Cans	0.3	0.3	0.4	0.8	0.1	0.1	0.1	0.1	0.4	1.0	0.3	1.0
CH-Stg-Assay	0.5	0.3	0.1	0.1	0.2	0.2	0.2	0.2	0.4	0.1	0.2	0.1
CH-Total[b]	0.8	0.7	0.6	1.6	0.4	0.3	0.4	0.3	0.9	1.8	0.9	2.0
Annual Total[b]	6.8	3.9	2.7	5.7	4.1	3.8	4.0	3.6	4.7	5.2	4.5	6.9
Lifetime, $M												
RH Waste[b]	141.2	76.1	49.5	94.5	86.7	81.4	83.8	75.5	88.8	79.6	84.2	114.1
CH Waste[b]	17.7	15.7	14.0	37.6	8.5	7.8	8.5	7.8	20.5	41.0	21.6	46.4
Total Life[b]	158.9	91.8	63.5	132.1	95.2	89.2	92.3	83.3	109.3	120.6	105.8	160.5

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) Total values are rounded from sum of detailed numbers given in Appendix B.

TABLE 7.3. Summary of TRUW and HAW Treatment Alternatives Lifetime Capital, Operating, and Decommissioning Costs for the Treatment Facility[(a)]

Cost Element	Cost by Alternative, $M											
	1	2	3	4	4A	4B	4C	4D	5	6	7	8
Capital	46.0	27.6	18.5	35.8	28.9	27.9	27.8	26.8	31.9	27.5	32.4	44.1
Operating	158.9	91.8	63.5	132.1	95.2	89.2	92.3	83.3	109.3	120.6	105.8	160.5
Decommissioning[(b)]	5.5	3.3	2.2	4.3	3.5	3.4	3.3	3.2	3.8	3.3	3.9	5.3
Total	210.4	122.7	84.2	172.2	127.6	120.5	123.4	113.3	145.0	151.4	142.1	209.9

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) Decommissioning costs are taken to be 12% of capital cost per DOE 1986.

dedicated trains. Transportation capital (i.e., casks and TRUPACTs) and operating and maintenance costs for TRUW and HAW are estimated using the unit factors (container capacity and life and costs, train speed, turnaround time, shipping costs, and security costs) given in U.S. DOE 1985b.

Shipment of LLW is assumed to be done using commercial truck carriers. Unit transportation costs for LLW are taken from McNair et al. (1984), with costs escalated to 1985 dollars.

Table 7.4 presents the annual and lifetime operating costs and the initial and lifetime capital costs for transporting the treated TRUW and HAW from the central treatment facility to the disposal facility. Details of transportation costs are in Appendix B.

Table 7.4 shows that total transportation costs are significant compared to the total treatment facility costs. The transportation costs are highly dependent on the treated waste volumes, and they exceed the total lifetime facility capital and operating costs for the alternatives with high volumes of treated wastes (Alternatives 1, 2, 3, and 5).

7.3 DISPOSAL COSTS

The TRUW and HAW from the central treatment facility are assumed to be disposed of in a deep geologic repository. Incremental LLW, where applicable (Alternative 4), is disposed of in a commercial facility. It was also assumed that the deep geologic repository disposal costs would be based on a repository receiving a total of 70,000 MTU of spent fuel.

A previous study (Ross et al. 1985) determined that disposal costs for TRUW were related to the HLW costs. This resulted from splitting the capital costs of the facility between the HLW and TRUW. As the volume of the TRUW was reduced, the HLW share of the repository capital costs increased. The disposal cost per unit volume of TRUW also increased with volume reduction, because the near, volume-independent capital costs are recovered by less waste.

Disposal costs were developed using RECON and cover construction, operation, and decontamination of the repository. The disposal costs for each of the alternatives in this study have been estimated based on the respective

TABLE 7.4. Transportation Costs for the TRUW and HAW Treatment Alternatives[a]

Cost Element	Cost by Alternatives, $M											
	1	2	3	4	4A	4B	4C	4D	5	6	7	8
Initial Capital, $M												
RH-Casks	107.5	35.0	12.5	7.5	12.5	12.5	12.5	12.5	42.5	10.0	15.0	12.5
CH-TRUPACTs	4.0	2.4	2.4	0.8	2.4	2.4	2.4	2.4	3.2	1.6	2.4	1.6
Total Capital	111.5	37.4	14.9	8.3	14.9	14.9	14.9	14.9	45.7	11.6	17.4	14.1
Annual Operating Costs, $M/yr												
Shipping/ Security	26.3	8.8	2.8	2.4[c]	2.7[c]	2.3	3.4[c]	3.0	10.3	2.2	2.8	2.7
Maintenance	5.7	2.0	.9	0.5	0.9	0.9	0.9	0.9	2.4	0.7	1.0	0.8
Total Annual[b] Operating	32.0	10.8	3.7	2.9	3.8	3.2	4.3	3.8	12.7	2.8	3.8	3.5
Lifetime, $M												
Capital[b]	223.0	74.8	29.8	16.6	29.8	29.8	29.8	29.8	91.4	23.2	34.8	28.2
Operating[b]	747.5	250.9	85.7	67.0[c]	83.1[c]	74.4	99.2[c]	89.6	295.4	65.7	87.4	80.2
Total Life	970.5	325.7	115.5	83.6[c]	112.9	104.2	129.1	119.4	386.8[c]	88.8	122.2	108.4

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) Total values are rounded from sum of detailed numbers given in Appendix B.
(c) Includes 0.5 $M/yr or 11.3 $M total lifetime LLW shipping costs.

volumes of RH and CH waste that will be disposed of in the repository. The costs of LLW disposal have been calculated and included in Alternative 4. The estimates for LLW disposal were calculated from the current (July 1985) LLW disposal cost schedule published by Chem-Nuclear Systems, Inc. at Barnwell, South Carolina.[a] The disposal cost for wastes disposed of in a deep geologic repository disposal were estimated from the previous disposal cost data (Ross et al. 1985). The referenced cost data were based on those for a basalt repository that adds overpacks for the RH wastes. A repository in basalt is expected to have somewhat higher costs than in other repository media (U.S. DOE, 1984).

The repository disposal cost data from Ross et al. (1985) were divided into CH and RH waste data, and a correlation between cost and volume was obtained for the seven sets of data. It was found that an equation of the form:

$$\text{costs} = a \sqrt{(\text{vol})} + b\ (\text{vol})$$

fits the data with a correlation coefficient of 0.96. Equations of this form were used for both the RH and the CH waste volumes (see Appendix B for details).

The heat loading of the melted fuel hardware, after being out of the reactor for 10 years, was estimated to be about 125 W/333-L canister for spent fuel hardware wastes from a melted pressurized water reactor (PWR), and 95 W/333-L canister for spent fuel hardware wastes from a melted boiling water reactor (BWR). These expected heat-generation levels are near the maximum acceptable for stacking in repository boreholes and may require some additional aging, particularly for the PWR wastes. However, for this study these heat levels were assumed to be low enough that they would not result in additional disposal costs related to the need for greater space to provide further separation of the waste packages to allow for adequate heat dissipation.

(a) The January 1986 changes in the LLW disposal act, which increase the disposal costs about $\$20/ft^3$, have not been included. These added costs would amount to about $75,000/yr for Alternatives 4, 4A, 4C.

The incremental LLW in Alternative 4 was estimated to contain less than 1 Ci/container, and would therefore have no surcharges applied to the wastes. The basic charge, including taxes, results in a cost of $189/208-L drum, which for Alternative 4 is an annual cost of about $80,000. For the 70,000-MTU base, the total cost is then about $1.9 million.

Application of the above information to the treated waste volume data in Section 6.0 for each of the eight primary alternatives results in the disposal costs shown in Table 7.5. The estimated costs show the importance of waste volume reduction on disposal costs. The currently proposed treatment in the MRS facility reduces waste disposal costs by about $700 M over the no-treatment costs (Alternative 1 versus Alternative 2). An additional $700 M or more could be saved in disposal costs by using a more effective volume reduction treatment (Alternatives 4, 6, and 8 versus Alternative 2). Alternative 4 has the lowest cost for disposal (as might be expected), and Alternative 6 has the second lowest cost. The $32 M cost difference between Alternatives 4 and 6 is mostly attributed to the decontamination of some materials in Alternative 4 and their less costly disposal as LLW. Improvements in the quality of the waste form with a 30% increase in final waste volume in Alternative 8 versus Alternative 4 increase the cost of disposal by about $90 M in Alternative 8.

Also note that the cost of RH wastes are a factor of 4 to 9 higher than the cost for disposal of CH wastes.

7.4 TOTAL LIFE-CYCLE COSTS

The total life-cycle costs (exclusive of R&D and repository siting development and engineering costs) for management of the TRUW and HAW from the 12 treatment alternatives are given in Table 7.6. The costs given in Table 7.6 are taken from Tables 7.1 through 7.5.

Table 7.6 shows that disposal accounts for the majority of total lifetime cost, ranging from 61% in Alternative 1 to 79% in Alternative 3 of the undiscounted total costs. Transportation costs range from 11% of total lifetime costs for Alternative 8 to 20% for Alternative 5 (except for 32% for Alternative 1). Treatment facility costs range from 7% of the total lifetime costs

TABLE 7.5. Repository and Disposal Costs for the Treatment Alternatives[a]

Cost Element	Undiscounted Cost by Alternatives, 1985 $M											
	1	2	3	4	4A	4B	4C	4D	5	6	7	8
RH Waste	1,851	1,162	624	451	509	519	618	624	1,254	474	603	529
CH Waste	203	165	119	78	111	112	111	112	182	88	128	91
LLW	--	--	--	2	2	--	2	--	--	--	--	--
Total	2,055	1,327	743	531	622	631	731	736	1,437	562	732	619

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calcualtions.

TABLE 7.6. Life-Cycle Costs for Management of the TRUW in the Treatment Alternatives[a]

Cost Element	Undiscounted Cost by Alternative, 1985 $M											
	1	2	3	4	4A	4B	4C	4D	5	6	7	8
Treatment Facility, $M	210	123	84	172	128	121	123	113	145	151	142	210
Transportation, $M	971	326	116	84[b]	113[b]	104	129[b]	119	387	89	122	108
Disposal, $M	2,055	1,327	743	531[c]	622[c]	631	731[c]	736	1,437	562	732	619
TOTAL	3,236	1,776	943	787	863	856	983	968	1,969	802	996	937

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations. However, values are rounded to agree with totals on the prior five tables.
(b) Includes 11.3 $M LLW shipping costs.
(c) Includes 1.8 $M for LLW disposal.

for the simple treatment alternatives (Alternatives 1 and 2) to 22% for the more extensive treatment alternatives (Alternatives 4 and 8). The costs of disposal and transportation account for 78% to 93% of the total costs, and their costs are strongly dependent on the final volumes of treated wastes. Therefore, there are major economic incentives for considering the more extensive treatment alternatives.

8.0 COMPARISON OF ALTERNATIVES

Previous sections have emphasized the identification and evaluation of TRUW and HAW treatment alternatives based on waste volumes, packaging, and analysis of the waste management system costs. The waste form characteristics (based on waste acceptance at the repository), and the waste treatment process characteristics (operational safety, process simplicity, status of technology) are discussed and compared in this section. The alternatives are then rated based on costs, waste form characteristics, and process characteristics.

8.1 WASTE FORM CHARACTERISTICS

The general requirements for the waste forms were reviewed in Section 4.0 with the regulatory requirements for waste disposal. Although geologic disposal in a federal repository is assumed in this study, the final disposal methods for TRUW and HAW have not been established. As noted in Section 4.0, the acceptability for disposal of any waste form cannot be stated with certainty, because detailed waste form requirements have yet to be established. However, the better the properties of the waste form, the greater the likelihood of its acceptance for disposal and the higher its rating in this evaluation.

Section 4.0 indicated that the waste form may be required to have specific characteristics, particularly for deep geologic disposal. The most significant characteristics that may be required for the waste form are:

- Low release rate of radionuclides from the waste form, especially during water contact, which is viewed as the most likely release mechanism following geologic disposal.
- No organic or combustible materials, (important because of potential organic complexing of actinides, which can lead to the acceleration of their migration from the repository).
- Immobilized particulates (to avoid release of material if a canister fails during handling or transportation, and to reduce potential release rates).

- No pyrophoric potential in the waste materials (important during waste package handling, transportation, and storage).
- Structural stability to assist in preventing mechanical failure of the canister, overpack, or container (<20% void volume in packages).
- The ability of the waste form to resist high radiation doses without degradation of the preceding five characteristics or generation of detrimental volumes of gas from radiolysis.

Five steps were carried out to assess the relative performance of the waste forms produced by each of the 12 treatment alternatives:

- Identify the waste forms.
- Rank each waste form.
- Assign a percentage weighting to each of the six waste form characteristics.
- Define a value of relative favorability for each waste form alternative.
- Determine the waste form value for each alternative.

First, the 18 different waste forms that would be produced by the eight waste treatment alternatives were identified. Each of these waste forms was then ranked according to the six waste form characteristics defined previously. The waste forms were ranked on a scale of 1 to 18 with the lowest numerical ranking being best. This was done in detailed discussions of the relative ranking of the waste forms until the authors reached a resolution. Several ranking methods were tried, including grouping the forms that had nearly the same characteristics and using a "relative worth" value rather than a ranking. In the end, it was felt that ranking the waste forms according to the six characteristics provided a sufficient separation in rankings. The authors also constructed and agreed on a percentage weighting for the relative importance of each of the waste form characteristics.

Table 8.1 lists the waste forms in alphabetical order and shows the results of the ranking and the relative percentage weightings for each waste

TABLE 8.1. Relative Weightings, Ranking, and Relative Worth Values of the 18 Waste Forms[(a)]

	Release Rate	Organic or Combustible	Particulates	Pyrophoricity	Structural Stability	Radiation Resistance	Waste Form[(b)] Form Value
Relative Weighting, %	50	15	15	10	3	7	
Waste Form							
Cement	7	9	9	1	7	10	721
Cement Containing Metals	8	8	8	8	6	9	801
Cement with Combustibles	9	11	10	6	8	14	947
Compacted Combustibles	15	17	15	15	15	16	1,537
Compacted HEPA Filters	16	14	16	14	14	13	1,523
Dried Resins	17	15	17	7	16	17	1,567
"Durable" Melted Metal	2	4	1	9	1	2	282
Highly Compacted Combustibles	12	16	12	13	13	15	1,294
Highly Compacted Dried Sludge	13	10	14	4	12	11	1,163
Highly Compacted HEPA Filters	14	13	13	12	11	12	1,327
Highly Compacted Metals	10	6	6	16	9	4	895
Hot Pressed "Durable" Oxides	1	1	3	2	3	6	181
Melted Metal	4	5	2	10	2	3	432
Melted Oxide Residues	5	2	4	3	5	7	434
Metal Pieces	11	7	11	17	17	5	1,076
Mixed Melted Wastes	6	3	5	5	4	8	538
Residues in Sulfur-Bonded Graphite	3	12	7	11	10	1	582
Untreated Wastes	18	18	18	18	18	18	1,800

(a) 1 = highest (best) rank; 18 = lowest (worst) rank.
(b) Obtained from the sum of the products of the relative weighting and waste form ranking for each characteristic.

form characteristic. Note that hot-pressed "durable" oxide was given the best overall product value in terms of the six waste form characteristics, and a "durable" metal was a good second. The least desirable form was the untreated waste, which ranked last in each of the characteristics. The dried and compacted materials were also expected to be poor performers.

The last step in the assessment was to combine the values for each of the waste forms generated by each treatment alternative into an "alternative waste form value." This was necessary to account for the different types and volumes of waste forms in each alternative and to provide a standard basis of comparison. This was done by multiplying the waste form value by its fractional volume and then summing the resulting values for each alternative. Table 8.2 lists the results of this combination and normalization of the waste form values. Alternative 1 provides a good example of the normalization procedure. The three waste forms generated in Alternative 1 are untreated wastes, cement, and dried resins. The untreated waste volume clearly dominates the volume, so the weighting for Alternative 1 is dominated by the untreated waste ranking. A simple averaging, which was considered and rejected as a normalizing process, would have given a significantly lower value because of the presence of a small volume of cement.

Note in Table 8.2, that the best waste treatment alternative from a waste form point of view is Alternative 8, which only produces durable metals and oxides. The worst is Alternative 1 with its high content of untreated wastes. Alternatives 4 and 6 both appear to have good waste form ratings even though the treatment processes were not specifically chosen for their waste form characteristics. Alternative 7 has a very similar value to Alternative 6, and the difference between them may not be significant. Alternatives 4A, 4B, 4C, and 4D have similar ratings to Alternatives 6 and 7. The use of cement as a final waste form has significantly raised the alternative 4A, 4B 4C, and 4D product ratings from Alternative 4. The use of cement in Alternatives 4C and 4D, rather than melted oxide in Alternatives 4A and 4B, also raised their ratings. Alternatives 2 and 5 also have very similar values that indicate less desirable properties. Note that what will be needed will be an acceptable waste form,

TABLE 8.2. Combination and Normalization of Treatment Alternative Waste Form Values

Alternative Number	Products	Waste Form Value	Waste Form Volume	Alternative Waste Form Value
1	Untreated Wastes	1,800	2,105	1,718
	Cement	721	174	
	Oried Resins	1567	2	
2	Metal Pieces	1,076	545	1,122
	Compacted Filters	1,523	258	
	Cement with Combustibles	947	39	
	Cement	721	179	
3	Highly Compacted Metals	895	119	915
	Highly Compacted Filters	1,327	68	
	Highly Compacted Combustibles	1,294	12	
	Highly Compacted Dried Sludge	1,163	1	
	Cement	721	157	
4	Melted Metal	432	99	433
	Melted Residues - Oxide	434	74	
4A	Melted Metal	432	74	620
	Melted Residues - Oxide	434	18	
	Cement	721	170	
4B	Melted Metal	432	84	613
	Melted Residues - Oxide	434	18	
	Cement	721	170	
4C	Melted Metal	432	74	657
	Cement	721	259	
4D	Melted Metal	432	84	650
	Cement	721	256	
5	Cement Containing Organics	1,537	436	1,139
	Cement Containing Metals	947	593	
	Cement	801	176	
6	Mixed Melted Wastes	582		582
7	Melted Metal	434	87	625
	Cement	801	131	
	Residues in Sulfur-Bonded Graphite	582	146	
8	"Durable" Melted Metal	282	107	227
	Hot Pressed "Durable" Oxides	181	129	

not necessarily the waste form with the highest rating. Critical cost and processing factors are also considered in the subsequent sections.

8.2 PROCESSING CONSIDERATIONS

The processes required for each waste treatment alternative were evaluated qualitatively according to their operational safety, process simplicity, and status of technology. A numerical method was then used to obtain an overall process ranking and a process value. The process values for each treatment alternative were totaled to obtain an overall process value for each alternative. The following subsections discuss the evaluation criteria and describe the numerical ranking method.

8.2.1 Operational Safety

The safety of each waste treatment alternative relative to the operational staff and the general public was considered with respect to chemical hazards, fire or explosions, mechanical hazards, electrical hazards, and radionuclide releases. All of the processes would be safe when implemented, but some of the processes have inherent safety concerns that would require additional safety provisions in the design or operation procedures.

Chemical hazards are judged based on the use or generation of hazardous materials such as acids, bases, respirable fines, toxins, etc. The processes selected for this study do not generally require these agents (although some of these agents may be generated during processing) and, as such, are relatively safe chemically.

Fire or explosion hazards could occur during handling of organic and combustible materials and the use of high-temperature processes. Process units that have a higher fire or explosion potential include the arc pyrolysis melter, incinerator, metal melter, oxide melter, and calciner.

Mechanical hazards are a concern where operating personnel work near mechanical equipment and high-pressure systems. Although most processes have some mechanical system, process units that have a large amount of mechanical operations are the shredder, compactors, presses, mixer grinders, and the in-drum cement mixer.

Electrical hazards are related to the amount of electrical power used. None of the alternatives should pose a major hazard to operating personnel because the electrical power is likely to be handled safely. Process units that are more electrical power intensive include the arc pyrolysis melter, metal melter, oxide melter, calciner, and hot press.

The potential for radionuclide release is related to generation of radioactive elements as particulates or gas. This is more of a concern with high-temperature processes that have a higher potential for volatilization of radionuclides. Process units that have increased potential for radionuclide release include the arc pyrolysis melter, metal melter, incinerator, oxide melter, calciner, and hot press.

The authors used the above-mentioned safety considerations to rank the process units from the safest to the least safe. The process ranking, as determined by the authors, is shown in Column 1 of Table 8.3. Simple process units, such as the in-drum grouter and the dryer, were judged to be inherently more safe. High-temperature process units, including the arc melter, metal melter, incinerator, and oxide melter, were judged less safe.

8.2.2 Process Simplicity

Each process was evaluated as to the complexity of both equipment and operations. Complex equipment may require more maintenance and repair and more care in operations than simpler systems. Process complexity also frequently shows up in increased cost of labor, process equipment, and facility space.

The rankings of process simplicity are shown in Column 2 of Table 8.3. The in-drum grouter, drum compactor, and dryer were considered to be less complex process units while the arc pyrolysis melter, incinerator, metal melter, oxide melter, and hot press were considered to be more complex.

8.2.3 Status of Technology

The time required for implementation of the technology, the cost of R&D, the availability of designs, and the operational experience are all related to the status of technology. The authors considered these factors in deriving a ranking of the processes in terms of status of technology. The result of the

TABLE 8.3. Ranking of the Waste Treatment Processes[a]

Rank	Operational Safety	Process Simplicity	Status of Technology	Overall Process Ranking
1	In-drum grouter	In-drum grouter	Dryer	Dryer
2	Dryer	Drum compactor	Drum compactor	Drum compactor
3	In-drum cement mixer	Dryer	Decontamination system	In-drum grouter
4	Shredder	In-drum cement mixer	Supercompactor	In-drum cement mixer
5	Size reduction system	Size reduction system	Off-gas system	Size reduction system
6	Drum compactor	Shredder	Calciner	Supercompactor
7	Supercompactor	Press	In-drum cement mixer	Shredder
8	Press	Mixer/grinder	In-drum grouter	Press
9	Decontamination system	Supercompactor	Press	Decontamination system
10	Separation system	Separation system	Incinerator	Off-gas system
11	Mixer/grinder	Decontamination system	Size reduction system	Calciner
12	Off-gas system	Calciner	Shredder	Separation system
13	Hot press	Off-gas system	Separation system	Mixer/grinder
14	Calciner	Hot press	Metal melter	Hot press
15	Oxide melter	Oxide melter	Hot press	Incinerator
16	Incinerator	Metal melter	Oxide melter	Oxide melter
17	Metal melter	Incinerator	Mixer/grinder	Metal melter
18	Arc pyrolisis melter	Arc pyrolysis melter	Arc pyrolysis melter	Arc pyrolysis melter

(a) 1 = highest (best) rank; 18 = lowest (worst) rank.

qualitative evaluation of the technology status is summarized in Column 3 of Table 8.3. The status of technology is most favorable for the dryer, drum compactor, decontamination system, supercompactor, and off-gas system; and is less favorable for the arc pyrolysis melter, mixer/grinder, oxide melter, hot press, and metal melter.

Many of the processes have been developed for other types of radioactive wastes, particularly defense TRUW and LLW where shredding, incineration, and cementing are being used. Development of technologies for both defense TRUW and LLW is expected to continue, reducing the amount of technology development needed for commercial TRUW and HAW. Timing of the technology for application to commercial fuel reprocessing does not appear to be a major concern; however, timing of the technology for spent fuel consolidation operations within the federal waste management system could be critical. The cost for R&D is expected to be small compared to the potential savings from implementation of the technology.

8.2.4 Overall Process Evaluation of Treatment Alternatives

The overall ranking of the processes is given in the last column of Table 8.3. This ranking is a composite of the three factors presented in the prior three columns.

A numerical weighting method was used to derive the final ranking and to obtain a process value for each of the 18 processes. Each process was assigned a number from 1 (best) to 18 (worst) for each evaluation category. The authors then gave each evaluation category a relative weighting, based on their combined judgment (operational safety = 20%, process simplicity = 50%, and status of technology = 30%). A process value for each process unit was then calculated by summing the product of the process ranking number and the evaluation category weights. Table 8.4 shows the assigned numbers and the resulting process value for each process unit.

The process values were used in the overall evaluation for the eight primary waste treatment alternatives. This final process evaluation for each alternative was performed by summing the process values for all of the CH and RH processes used in each treatment alternative. Table 8.5 shows the CH and RH

TABLE 8.4. Process Values for Each Process[a]

Process	Operational Safety[b]	Process Simplicity[b]	Status of Technology[b]	Process Value[c]
Arc pyrolysis melter	18	18	18	1,800
Calciner	14	12	6	1,060
Decontamination system	9	11	3	820
Drum compactor	6	2	2	280
Dryer	2	3	1	220
Hot press	13	14	15	1,410
In-drum cement mixer	3	4	7	470
In-drum grouter	1	1	8	310
Incinerator	16	17	10	1,470
Metal melter	17	16	14	560
Mixer/grinder	11	8	17	1,130
Off-gas system	12	13	5	1,040
Oxide melter	15	15	16	1,530
Press	8	7	9	780
Separation system	10	10	13	1,090
Shredder	4	6	12	740
Size reduction system	5	5	11	680
Supercompactor	7	9	4	710

(a) 1 = highest (best) rank; 18 = lowest (worst) rank (values come from Table 8.3).
(b) Relative weighting for operation safety = 20; process simplicity = 50; and status of technology = 30.
(c) Process values are the sums of the relative weighting multiplied by the ranking value (i.e., 18 x 10 + 18 x 10 + 18 x 10 = 1,800).

processes and the total numerical process value calculated for each treatment alternative. The relative process values are shown with the no-treatment alternative having the best process value. The next-best treatment alternatives are the MRS Reference, supercompaction, and cementation. Arc pyrolysis and melting is next in order of process desirability. The lowest process value

TABLE 8.5. Relative Process Values[(a)]

Treatment Option	CH Processes: Process Unit	CH Value	CH Sum	RH Processes: Process Unit	RH Value	RH Sum	Total Process Value
1. No Treatment			0	In-drum cement mixer	470	690	690
				Dryer	220		
2. MRS Reference	Size reduction system	680	960	Drum compactor	280	750	1,710
	Drum compactor	280		In-drum cement mixer	470		
3. Supercompaction	Size reduction system	680	1,180	Compactor	280	1,210	2,390
	Compactor	280		Dryer	220		
	Dryer	220		Supercompactor	710		
4. Maximum Volume Reduction	2 size reduction systems	1,360	7,230	Separation system	1,090	8,930	16,160
	Separation system	1,090		Shredder	740		
	Shredder	740		Incinerator	1,470		
	Incinerator	1,470		Off-gas system	1,040		
	Off-gas system	1,040		Decontamination system	820		
	Oxide melter	1,530		Oxide melter	1,530		
				Metal melter	1,560		
				Size reduction system	680		
4A. Maximum Volume Reduction	Separation system	1,090	1,090	Separation system	1,090	8,250	9,340
				Shredder	740		
				Incinerator	1,470		
				Off-gas system	1,040		
				Decontamination system	820		
				Oxide melter	1,530		
				Metal melter	1,560		
4B. Maximum Volume Reduction	Separation system	1,090	1,090	Separation system	1,090	7,430	8,520
				Shredder	740		
				Incinerator	1,470		
				Off-gas system	1,040		
				Oxide melter	1,530		
				Metal melter	1,560		
4C. Maximum Volume Reduction	Separation system	1,090	1,090	Separation system	1,090	7,190	8,280
				Shredder	740		
				Incinerator	1,470		
				Off-gas system	1,040		
				Decontamination system	820		
				In-drum cement mixer	470		
				Metal melter	1,560		

TABLE 8.5. (contd)

Treatment Option	CH Processes: Process Unit	CH Processes: Value	CH Processes: Sum	RH Processes: Process Unit	RH Processes: Value	RH Processes: Sum	Total Process Value
4D. Maximum Volume Reduction	Separation system	1,090	1,090	Separation system	1,090	6,370	7,460
				Shredder	740		
				Incinerator	1,470		
				Off-gas system	1,040		
				In-drum cement mixer	470		
				Metal melter	1,560		
5. Cementation	Size reduction system	680	1,890	Shredder	740	1,670	3,560
	Shredder	740		2 in-drum grouters	460		
	In-drum cement mixer	470		In-drum cement mixer	470		
6. Arc Pyrolysis and Melting	2 size reduction systems	1,360	4,200	Arc melter	1,800	3,520	7,720
	Arc melter	1,800		Off-gas system	1,040		
	Off-gas system	1,040		Size reduction system	680		
7. Sulfur-Graphite	Size reduction system	680	6,460	Separation system	1,090	7,810	14,270
	Separation system	1,090		Shredder	740		
	Shredder	740		Incinerator	1,470		
	Incinerator	1,470		Off-gas system	1,040		
	Off-gas system	1,040		Mixer/grinder	1,130		
	Mixer/grinder	1,130		Press	780		
	In-drum grouter	310		Metal melter	1,560		
8. Highest-Quality Waste Form	2 size reduction systems	1,360	10,000	Separation system	1,090	10,200	20,200
	Separation system	1,090		Shredder	740		
	Shredder	740		Incinerator	1,470		
	Incinerator	1,470		Calciner	1,060		
	Calciner	1,060		Off-gas system	1,040		
	Off-gas system	1,040		Mixer/grinder	1,130		
	Mixer/grinder	1,130		2 hot presses	2,110[b]		
	2 hot presses	2,110		Metal melter	1,560		
				Size reduction system	680		

(a) 1 = highest (best) rank; 18 = lowest (worst) rank.
(b) Where two like processes are required, the process value is increased by 50% for that process.

treatment alternatives are the MVR reduction, sulfur-bonded graphite, and highest-quality waste form alternatives. Alternatives 4A, 4B, 4C, and 4D all have improved values over Alternative 4, because of the elimination of several of the process units originally in Alternative 4.

8.3 COMBINED ALTERNATIVE RATINGS

This section discusses combining the waste form values, process values, and costs for each of the alternatives, with respective costs or values from Sections 7.5, 8.1, and 8.2. Because the values are based on different scales and have different ranges, they are not directly comparable. Therefore, we first divided all of the values by the minimum value for that characteristic to obtain a ratio of relative value. A summary of these results is shown in Table 8.6, where it can be noted that costs, waste form, and process values differ by up to a factor of 4.61, 7.67, and 29.28, respectively. Using an equation of the form "Rating = a (value) - b" we have spread the values for each of the characteristics on a rating scale of 1 to 100. The best

TABLE 8.6. Summary of Evaluation Characteristic Values and Their Normalized Relative Values

Alternative	Life-Cycle Costs $M	Waste Form Value	Process Value	Relative Cost	Relative Waste Form Value	Relative Process Value
1	3,236	1,718	690	4.11	7.57	1.00
2	1,776	1,122	1,710	2.26	4.94	2.48
3	943	915	2,390	1,29	4.03	3.46
4	787	433	16,160	1.00	1.91	23.42
4A	863	620	9,340	1.10	2.73	13.54
4B	856	613	8,520	1.09	2.70	12.35
4C	983	657	8,280	1.25	2.89	12.00
4D	968	650	7,460	1.23	2.86	10.81
5	1,969	1,139	3,560	2.50	5.02	5.16
6	802	582	7,720	1.02	2.56	11.19
7	996	625	14,270	1.27	2.75	20.68
8	937	227	20,200	1.19	1.00	29.28

alternative was rated 1 and the least desirable alternative was rated 100. Values of a and b were selected to provide this spread. An equation of the form "Rating = a (value)" was also tested to increase the maximum value to 100, and there were only very minor differences in the relative positions of the alternatives. Table 8.7 summarizes of the final ratings and the sum of the three rating values for each alternative. Note that Alternative 6 has the lowest and best rating, followed by Alternatives 3 and 4B.

The total ratings in Table 8.7 assumed equal weighting for costs, waste form characteristics, and process characteristics, but cases can be made for different weights, and several sets of weights were investigated. These are contained in Table 8.8 where the three best ratings for each of the weights have been underlined. Note that Alternative 6 has one of the best ratings for nearly all of the weighted characteristics. The no-treatment alternative is only attractive if major weight is given to the process rating. The MRS facility alternative is likewise favored if the process rating is given the higher

TABLE 8.7. Comparative Ratings for Cost, Waste Form Characteristics, and Process Characteristics, and Their Sums

Alternative	Cost Rating	Waste Form Rating	Process Rating	Total[a] Rating
1	100	100	1	201
2	41	60	7	108
3	7	47	10	64
4	1	15	79	95
4A	4	27	45	76
4B	4	27	41	71
4C	9	30	40	78
4D	7	29	36	73
5	49	62	16	126
6	2	25	37	63
7	9	27	70	107
8	7	1	100	108

(a) Based on equal weight for cost, waste form, and process.

weighting. This is consistent with the design for the MRS facility, which was based primarily on process experience and availability. The supercompaction alternative is generally favored except in cases where waste form rating is weighted higher. The MVR alternative (Alternative 4) and Alternatives 4A and 4B do well under most balanced weightings and when cost is weighted high. Cementation is only attractive when process is weighted high, and then it is a slim third choice. The arc pyrolysis and melting alternative is the definite best choice in many cases and is nearly always one of the better choices irrespective of the weightings. The sulfur-bonded graphite alternative does not excel under any of the alternatives. The highest-quality waste form alternative is first choice when the waste form value is weighted high, as might be anticipated. The evaluation of the additional alternatives of Alternative 4 have very similar ratings, and many of the differences may not be significant; however, these results indicate that it is generally worthwhile to avoid treatment of the precemented wastes and to look more carefully at decontamination before decontamination is implemented. Also, the melting of the residues and oxide materials is favored over cementation.

Under the equal relative weighting scheme supercompaction, MVR with melting only, and arc pyrolysis and melting are the three best alternatives. It is interesting to note that at least one of the three is selected regardless of the weightings given to waste form, process, and costs. This implies that if those three processes were available, one would be a desirable system regardless of the weightings of the characteristics.

TABLE 8.8. Ratings with Weightings for Costs, Waste Form Characteristics, and Process Characteristics

Relative Weights											
	Cost	1	1	2	2	1	4	1	9	1	1
	Waste Form	1	2	2	1	4	1	1	1	9	1
	Process	1	2	1	2	1	1	4	1	1	9
Alternative		Rating									
1.	No Treatment	201	303	401	303	501	501	206	1,001	1,001	213[a]
2.	MRS Reference	104	174	209	155	288	231	128	436	588	161
3.	Supercompaction	66	121	118	81	205	85	95	120	440	146
4.	MVR with Decontamination	95	390	112	177	141	100	334	108	216	732
4A.	MVR with Decontamination and Melting	76	148	107	125	157	88	211	108	292	436
4B.	MVR with Melting Only	72	140	103	117	153	84	195	104	288	400
4C.	MVR with Decontamination and Cementing	79	149	118	128	169	106	199	151	319	399
4D.	MVR with Cementing Only	72	137	108	115	159	93	180	128	304	360
5.	Cementation	124	205	238	192	313	274	175	519	623	256
6.	Arc Pyrolysis and Melting	63	126	91	103	139	70	175	81	264	360
7.	Sulfur-Bonded Graphite	106	203	142	185	186	134	316	181	320	667
8.	Highest-Quality Waste Form	107	209	116	215	110	129	408	164	115	908

(a) The best three alternatives for each set of weights are underlined.

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APPENDIX A

TREATMENT ALTERNATIVES FOR ANTICIPATED WASTE TYPES

APPENDIX A

TREATMENT ALTERNATIVES FOR ANTICIPATED WASTE TYPES

The authors considered a wide variety of treatment processes that could be applied to each of the waste types. Treatment process flow diagrams were prepared for each of the major wastes types and are discussed in this section. Many of the potential treatment processes identified in the subsections below have been demonstrated for TRUW and HAW treatment, and they appear to be technically possible.

A.1 HEPA FILTERS

Because the HEPA filters comprise the largest volume of waste and consist of a composite of metal or wood, combustibles, and fiber glass media, they were considered most extensively. Figure A.1 shows the potential treatment alternatives for HEPA filters.

The first basic treatment choice is to treat the total filter or to separate it into frames and glass media, or frames, glass media, and polyurethane sealant. For treating the total filters, the treatments are divided into no treatment, pretreatment, compaction, melting, and incineration plus grouting. Any pretreatment would be to prepare the filters for subsequent treatment. Shredded filters have also been treated by grouting or cementing. Compaction, a low-technology, mechanical process, can be used effectively on HEPA filters to reduce their volume because of their low initial bulk density. However, supercompaction or cryogenic cracking (which would require the filters to be cooled near liquid-nitrogen temperatures and then compacted) were also identified as possibilities. Melting by any of several different techniques was also considered, but is difficult because of the presence of the organics in the polyurethane and glass media. The organics (polyurethane or other sealants, binders, and wood) can be incinerated as a preparatory step for melting or other treatments.

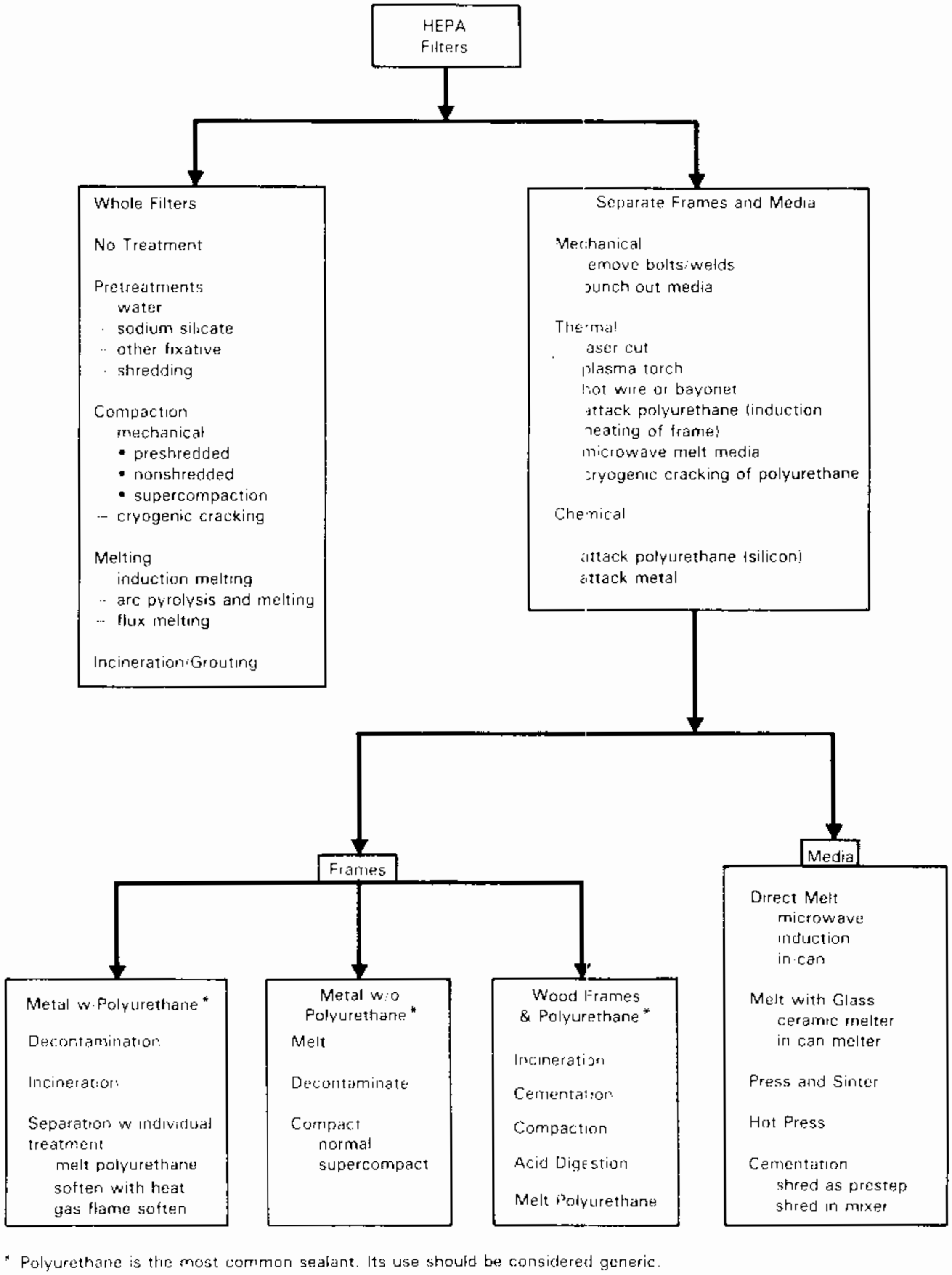

FIGURE A.1. Potential Treatments for HEPA Filters

Several approaches were identified for the separation of the pleated filtration glass media from the frames and these approaches have been grouped into mechanical, thermal, and chemical processes. The glass media can be removed mechanically by disassembling the filters or by punching out the glass media with a press. The media could be removed thermally by locally melting the sealant and/or media next to the frames. A laser, plasma torch, or hot wire could supply the heat. The polyurethane that bonds the media to the frames could be degraded by high temperatures, possibly by induction heating of the metal frames, or by extreme cold (cryogenic temperatures), which would make the polyurethane brittle and subject to fracture. Glasses can be heated by microwaves, which may make it possible to melt the fiberglass media from the frames. Concepts were also identified for the potential chemical destruction of the polyurethane or attack of the metal frames. However, these last treatment approaches would have the potential for generating large secondary waste streams.

Once the filter media have been separated from the remainder of the frame, they can be treated by several methods including melting, pressing and sintering, hot pressing, and cementing. Because the media are glass fiber, they could be consolidated by remelting. A variety of melting techniques is available, including microwave, induction, and thermal radiation heat (in-can vitrification). The media could also be mixed with other glass and melted by HLW vitrification technology. Experience with glass powders implies that the media could be consolidated at a moderate temperature (~600°C) by either pressing and sintering or hot pressing. Incorporation of the media into cement either directly or with pre-shredding has also been proposed. In the selection of the treatment method it should be remembered that the media typically contain about 5 wt% of organics.

The residual frames without the media can be treated directly, or the polyurethane can be separated from the frame. For the metal frames with polyurethane sealant, it may be possible to decontaminate them both together, destroy the polyurethane by incineration, or separate the polyurethane from the metal. It is considered unlikely that the residual fibrous media could be decontaminated directly, but no test results are available to support this judgment. Methods considered for separation of the frames from the media were based on the concept of heating and softening or melting the polyurethane binder. If the polyurethane with the residual media can be removed from the frame, the frame can be melted, decontaminated, or compacted to reduce the volume of waste.

HEPA filters with wooden frames, typically used only to filter aerosols with low radiation levels, are generally CH, and could be treated by incineration, cementation, compaction, or acid digestion.

These potential alternatives for treating HEPA filters cover a broad spectrum of methods. Because all of them could not be considered in detail in this study, the collective engineering judgments of the authors were used to select the treatment steps to receive further consideration, as discussed in Section 6.0.

A.2 SPENT FUEL HARDWARE

The conceptual design of the MRS facility involves a spent fuel hardware shredding system that is almost integral with the fuel rod consolidation system. Because of this, except for the heavy pieces, which are cut up without shredding, the as-generated waste form for the spent fuel hardware was assumed to be shredded in the spent fuel consolidation facility. Although shredding is not necessarily required for all subsequent treatment methods, it does not eliminate any processing alternatives and provides a convenient form for handling. The spent fuel hardware is the second of the two major waste streams and is highly radioactive so it is RH. The major treatment alternatives, shown in Figure A.2, include:

- no further treatment except loading into disposal canisters;
- compaction by conventional compactors (about 1,000 psi), supercompaction at pressures of about 10,000 psi, or hot pressing;
- melting with or without alloying agents (either to lower the melting point or to increase the chemical durability), or using a thermite reaction and the metallic waste's own pyrophoricity;

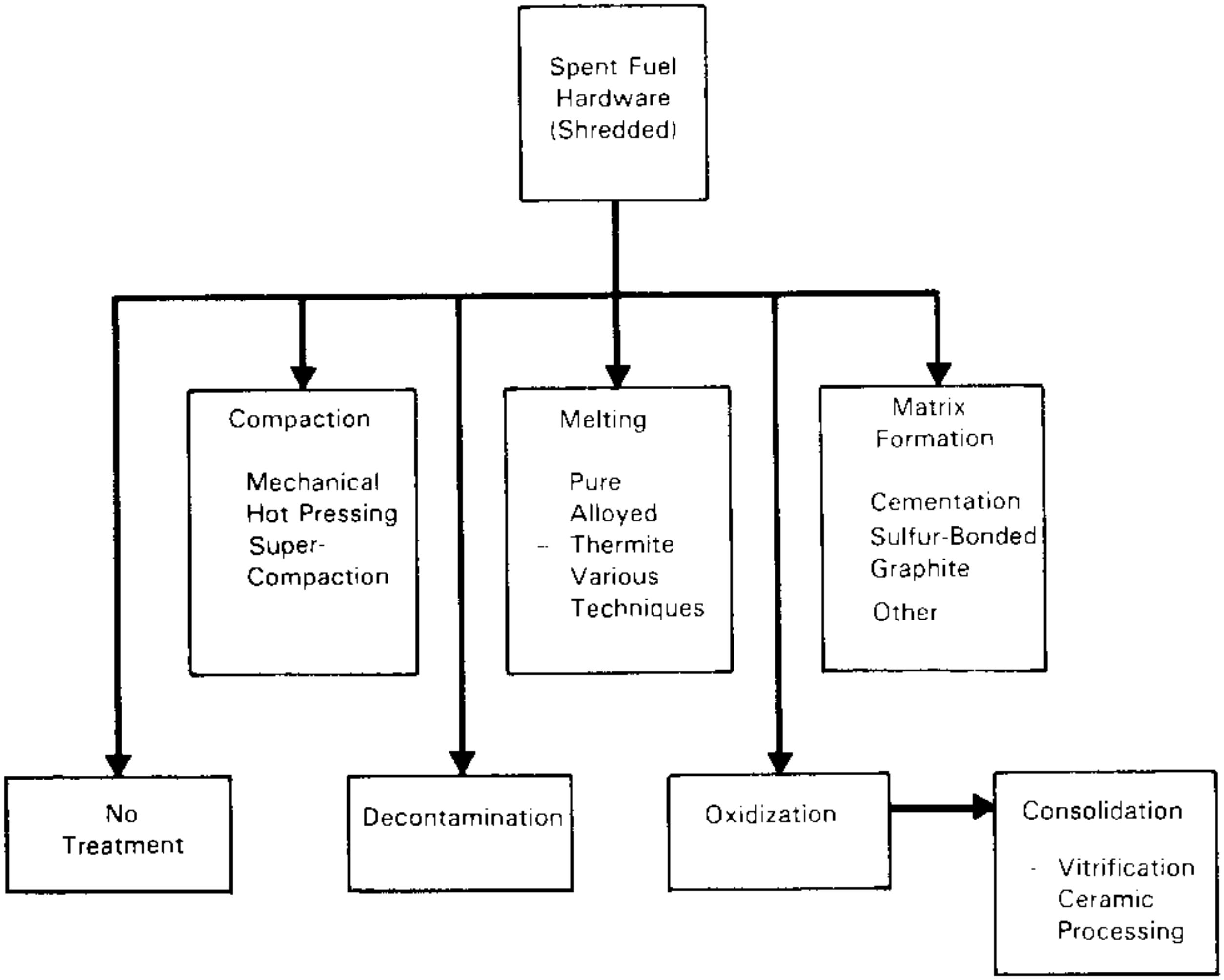

FIGURE A.2. Potential Treatments for Shredded Spent Fuel Hardware

- incorporation of the shredded hardware into a matrix of cement, or sulfur-bonded graphite or other durable material;
- decontamination to remove surface activity; and
- oxidization of the metals followed by their treatment as oxides, by incorporating them into either a glass or an oxide ceramic.

The compaction alternatives will provide significant volume reduction with minor improvements in final waste form quality. The melting alternatives will give the greatest volume reduction and greatly improve the waste form quality. The addition of other materials to form a more durable metal is also possible.

Melting will require high-temperature processing with the potential for vaporization of some radionuclides. Matrix encapsulation will result in some volume increase but may provide some improvement in waste form properties. Decontamination will not be effective because much of the activity, caused by neutron activation, is distributed throughout the metal and not just on its surface. Oxidation will require extra processing but may provide some volume reduction and stabilization of the materials. Oxidation will also reduce the theoretical density of the waste form and increase its total mass and volume.

A.3 FAILED EQUIPMENT

In this study, failed equipment is considered to be metallic. Equipment such as electric motors, which also contain some organics, are considered to be a mixed waste. The first choices for handling failed equipment (see Figure A.3) are:

- no further treatment except to package it as generated,
- repair and reuse when possible (attractive because it reduces the waste quantities), and
- prepare for further treatment (pretreatment).

Pretreatment, if selected, could include shredding or other size reduction and segregation for specific treatments of the subclasses. Following pretreatment, the wastes could be compacted, melted, incorporated into a matrix, or decontaminated. The compaction, melting, and matrix formation treatments are similar to the spent fuel hardware alternatives discussed previously. The decontamination alternative is frequently more attractive for failed equipment because failed equipment has only surface contamination and decontamination may reduce radioactivity levels sufficiently to allow for treatment as CH wastes or disposal of the equipment as LLW. Decontamination could be applied to the total piece of equipment or to selected sections of the failed equipment.

A.4 COMBUSTIBLES

Combustibles are generally a mixture of cellulose, plastics, and rubbers. Figure A.4 shows the various treatment alternatives. As for all other

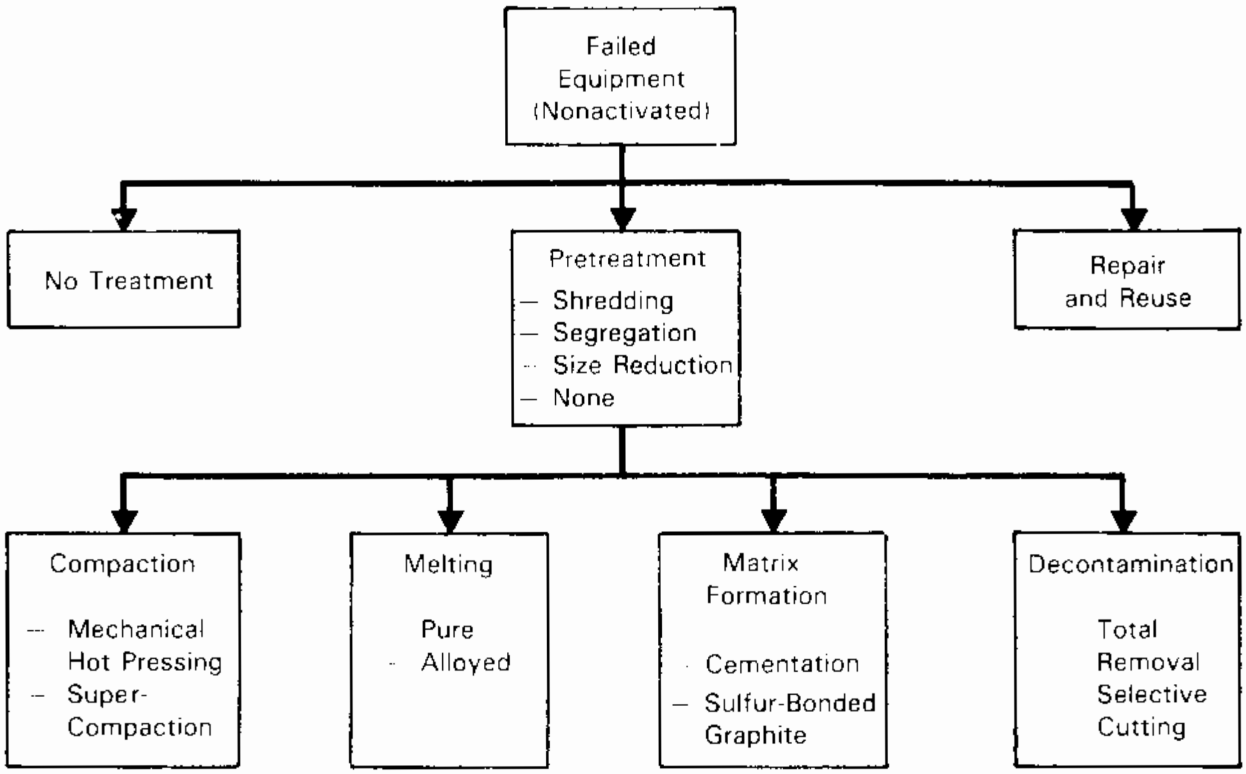

FIGURE A.3. Potential Treatment for Failed Equipment

waste types, the simplest treatment is no treatment. Pretreatment is considered desirable for most treatment alternatives, and can consist of shredding and/or incineration. The major treatment alternatives following pretreatment are:

- compaction by either conventional or supercompaction techniques (may include a "warm" pressing [e.g., at 100 to 200°C] for the plastic materials to allow them to creep and avoid spring-back);
- incineration to reduce the mass and eliminate combustibility;
- acid digestion is (an alternative to incineration for some waste types but is not attractive for wastes with a high noncombustible or PVC content);
- decontamination of some wastes where it would reduce the radioactivity levels of the TRUW to LLW and concentrate the activity into a much smaller volume for subsequent treatment; and

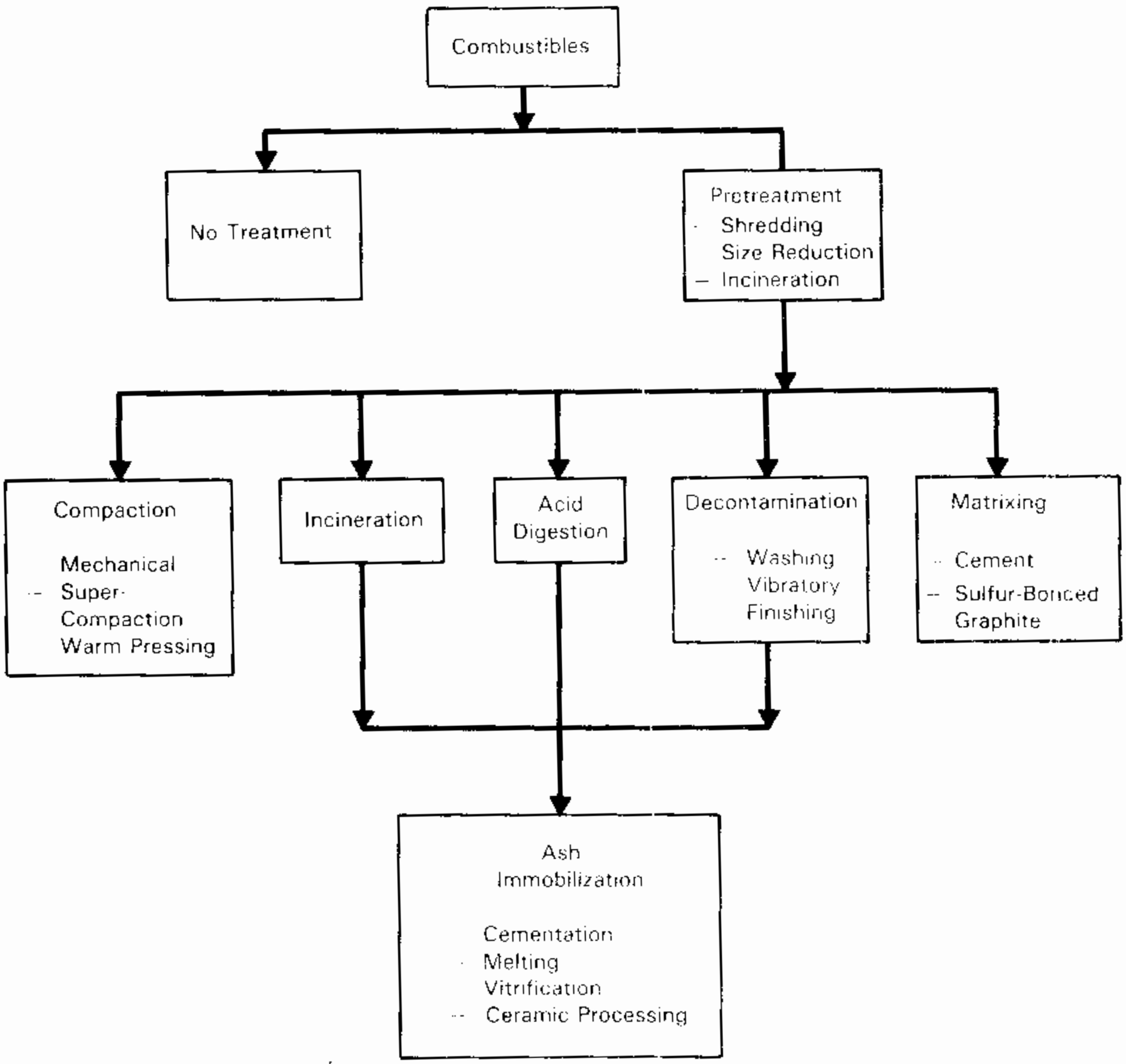

FIGURE A.4. Potential Treatment for Combustible Wastes

- incorporation of the wastes into a matrix such as cement or sulfur-graphite either before or after incineration.

Treatment of the wastes by incineration, acid digestion, or decontamination results in a residue that must also be solidified. Because the residues could be considered a ceramic, a variety of alternatives can be considered. The most common methods would be cementation, melting, and vitrification.

A.5 MIXED COMBUSTIBLES AND PROCESS FILTERS

Mixed combustibles and process filters are a combination of organics, metals, and oxides. They may simply be placed in a canister as generated or combined with other wastes such as electrical motors or pumps. Because many of the waste form and treatment concerns about mixed combustibles are similar to those for HEPA filters, the potential treatment alternatives are similar. Figure A.5 shows the various alternatives identified. The no-treatment and pretreatment alternatives are the first consideration. Pretreatments could be used to reduce the size of the waste pieces or to separate the organic materials from the remainder of the waste. Further treatments of mixed combustible wastes could include incorporation into a matrix, incineration, melting, and treatment of the separated metals, as discussed in Section A.3. The incorporation of the wastes into a matrix would modify the waste form performance characteristics. Two possible matrices considered in this study are cement and sulfur-bonded graphite, but others are possible. If the wastes are incinerated, the organic fraction would be driven off, and the residue could then be separated into metal and ash. The metals could be treated by the same processes as the failed equipment and the ash could be treated in the same manner as other ash from combustible wastes (see Section A.4). Direct melting would require a melter capable of handling all of the different materials. The Idaho National Engineering Laboratory (INEL) considered a slagging pyrolysis for such wastes but rejected it because of process difficulties (Tait 1983). An arc pyrolysis and melting system is proposed in this study and may have application for these wastes. Other melting systems, such as a plasma arc, may also be possible.

A.6 RESINS

Ion exchange resins are used to extract radioactive materials from process solutions and are usually designed to remove specific ions. The resins can he organic, inorganic, or a combination of the two, so treatment must consider this potential variability. The easiest treatments are to package them as as-generated resins or to simply dry them before packaging. Resins could be incorporated into a matrix such as cement or sulfur-bonded graphite, melted, or

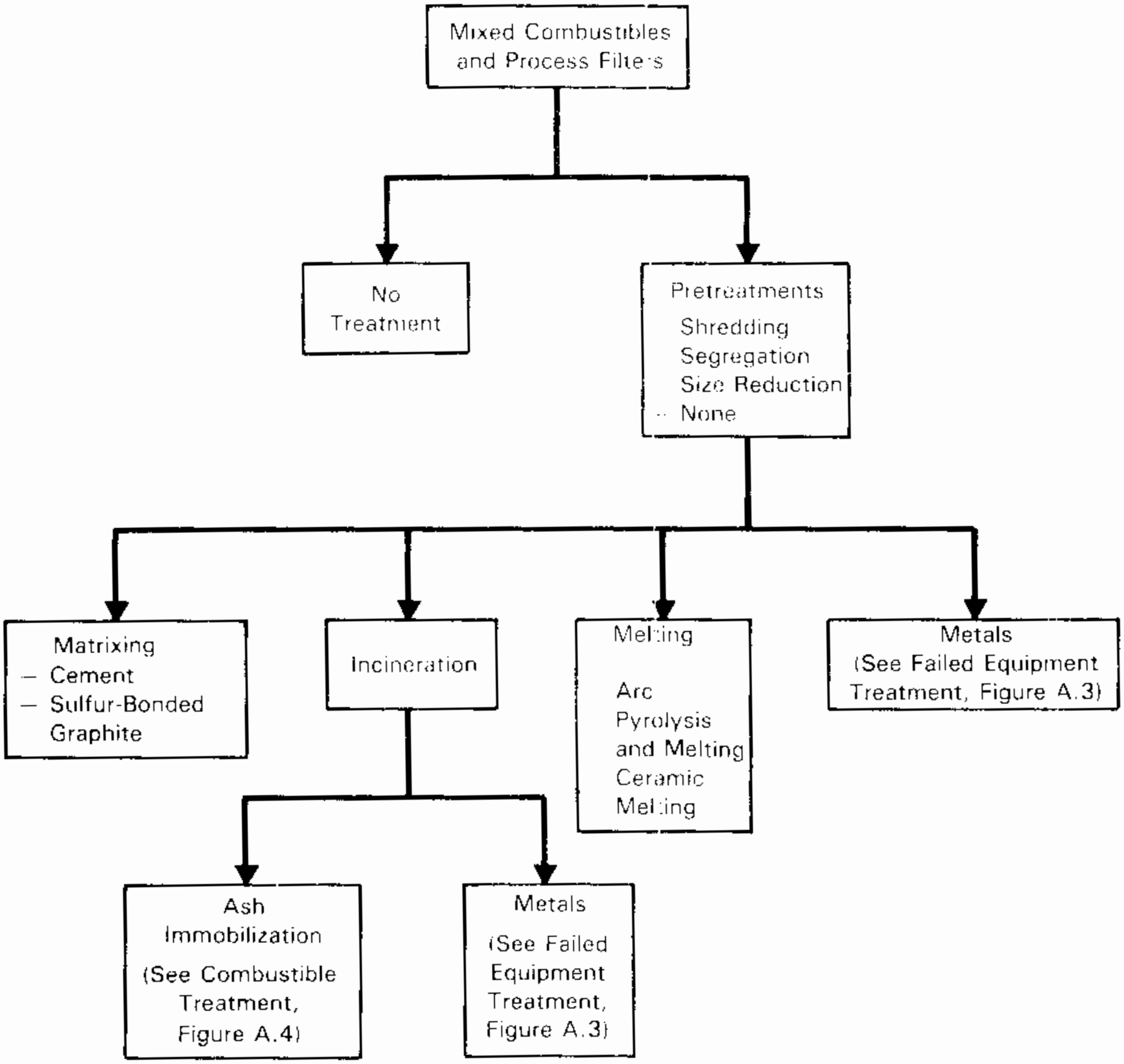

FIGURE A.5. Potential Treatments for Mixed Combustibles and Process Filters

pyrolyzed/incinerated. If the resins are totally inorganic, they could be densified as ceramics by hot pressing (see Figure A.6).

A.7 SOLUTIONS AND SLUDGES

Solutions and sludges result from the concentration of materials in liquid wastes and are generally inorganic. The alternatives identified for treating

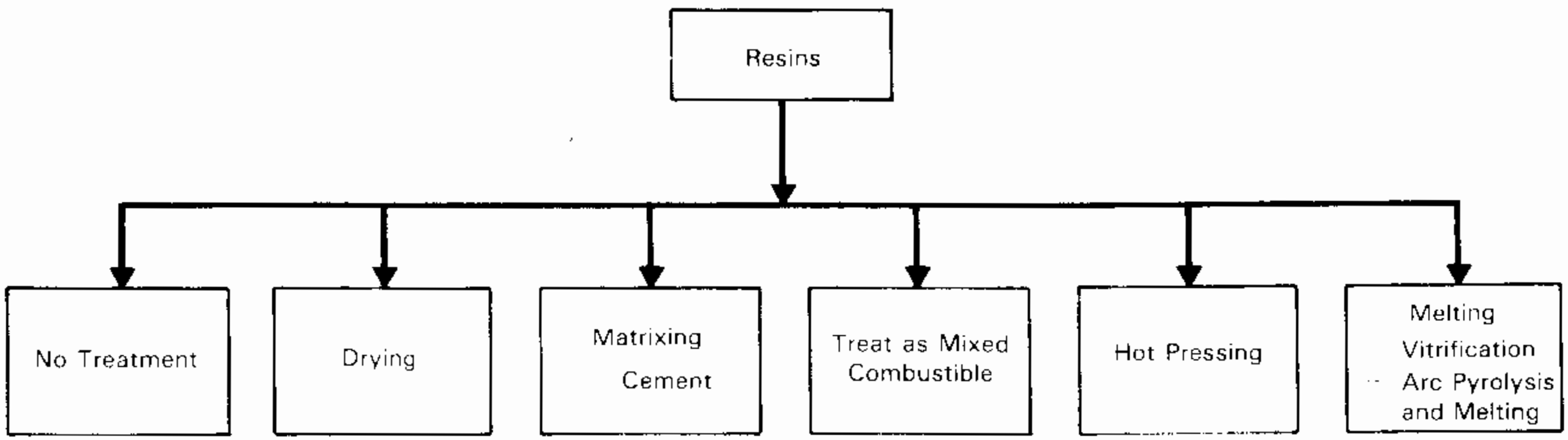

FIGURE A.6. Potential Treatment for Resins solutions and sludges are shown in Figure A.7. The no-treatment alternative is not viable because wastes will have to be solidified for transportation and probably for disposal. Because of this, the only solutions and sludges at the central treatment facility are those generated within the facility. The wastes could be dried by several techniques or cemented directly. If the wastes are dried, they could be given additional treatments to consolidate or immobilize them using compaction, melting, ceramic processing, or cementation.

A.8 CEMENT RUBBLE

Most cement rubble would come from the decontamination and decommissioning of processing facilities other than the central treatment facility. No treatment is a primary alternative for this waste, but the wastes could be reduced

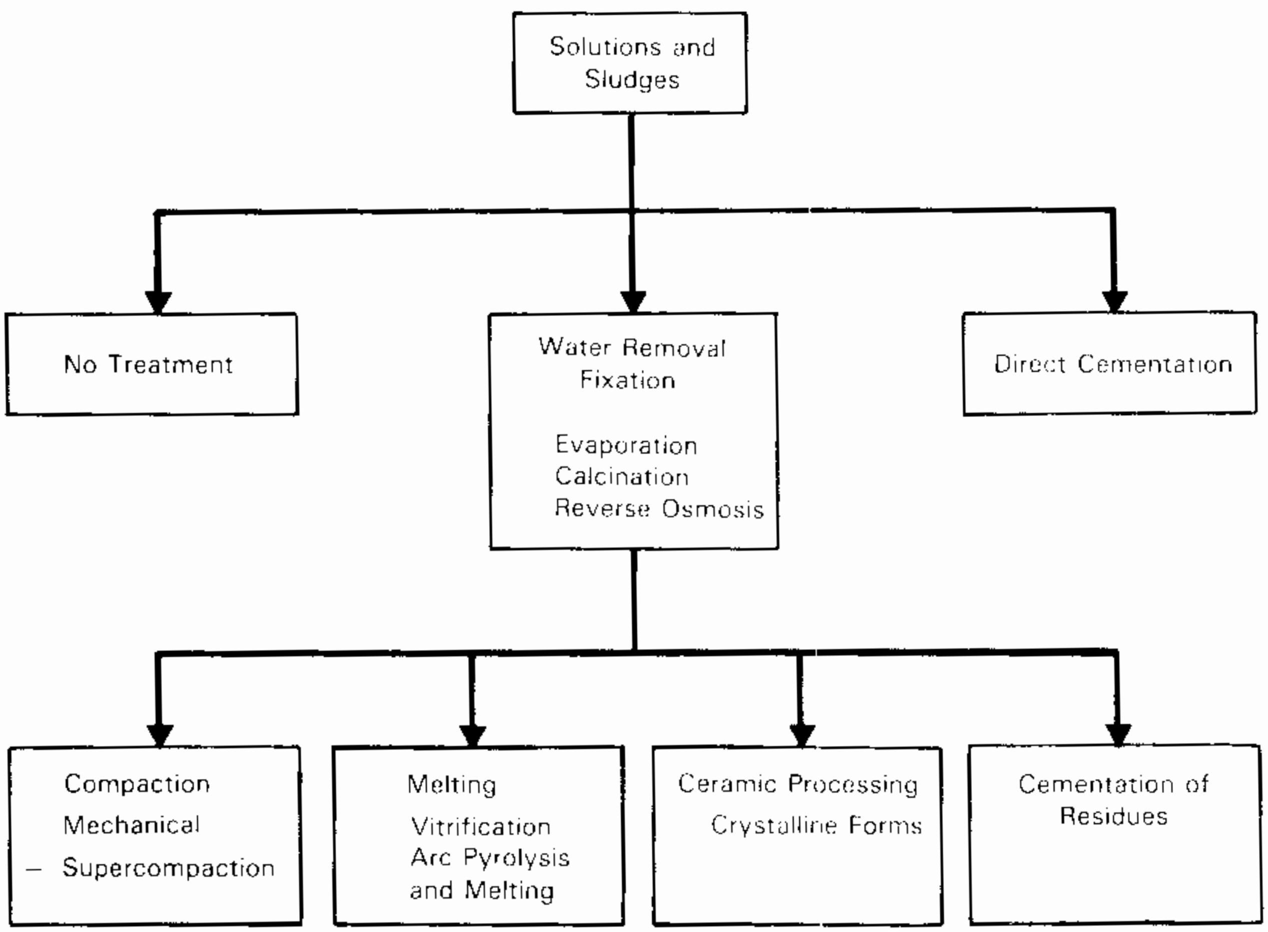

FIGURE A.7. Potential Treatments for Solutions and Sludges in volume by supercompaction or melting. Cement rubble could be further immobilized by incorporating it into a cement or other matrix, or possibly by calcining and recementing it into a monolithic form. These alternatives are shown in Figure A.8.

A.9 CEMENTED WASTES

Cemented wastes would be received from other commercial facilities. No treatment is an attractive alternative for these wastes because cement is a reasonably good waste form. However, if additional treatment is necessary, it would probably start with the crushing of the cement to reduce the size of the waste form and to facilitate other processing. Two alternatives that identified additional processing are to: 1) melt the cement, which would dehydrate it and increase its density; and 2) first calcine the cement, then densify it using a ceramic process such as hot pressing. These alternatives are illustrated in Figure A.9.

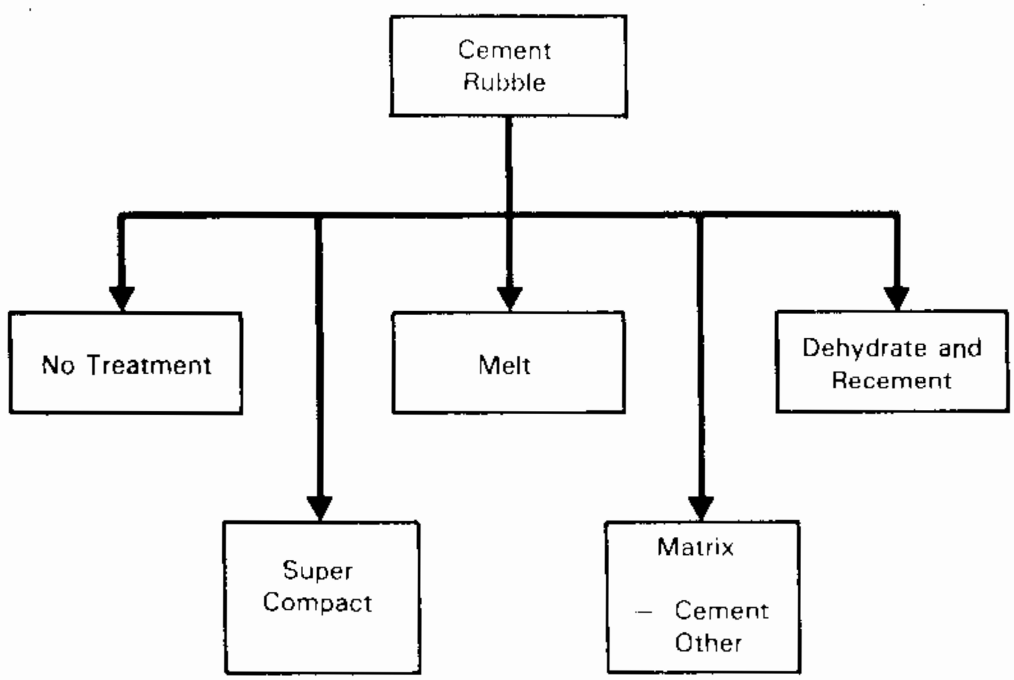

FIGURE A.8. Potential Treatments for Cement Rubble

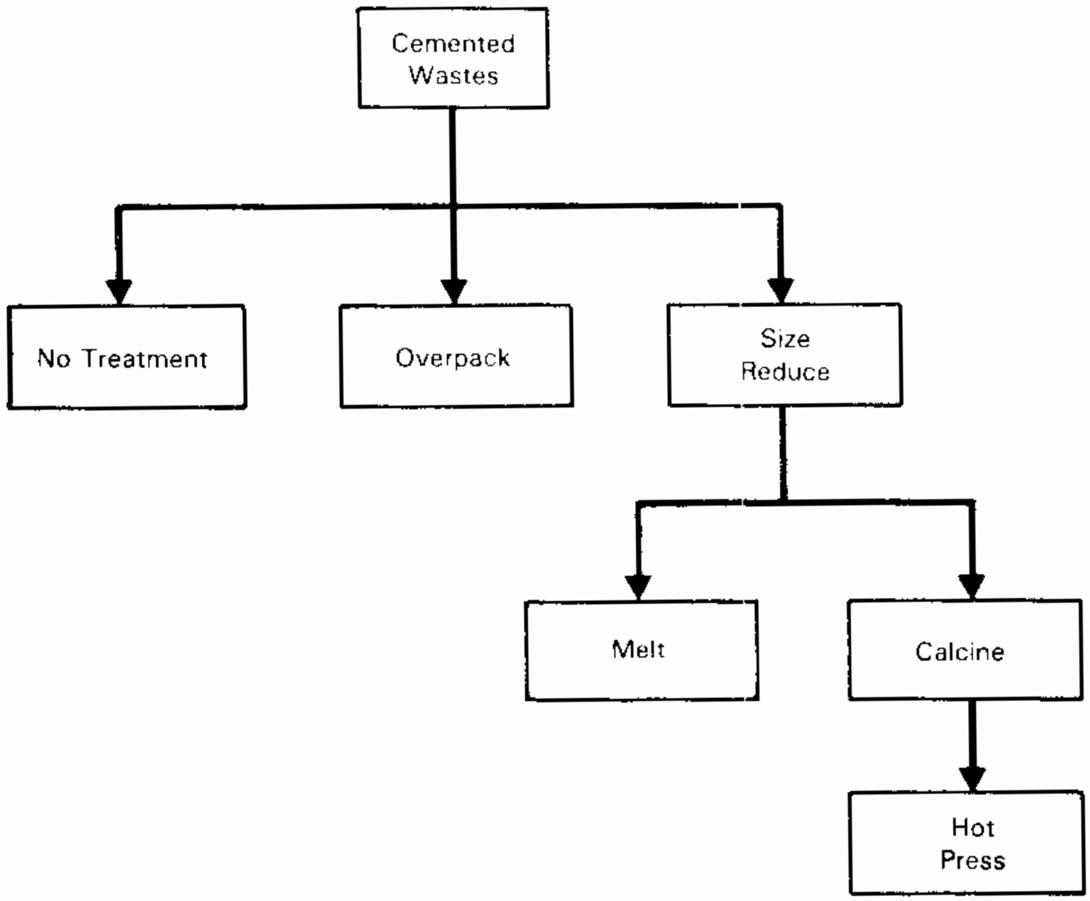

FIGURE A.9. Potential Treatments for Cemented Wastes

A.10 REFERENCES

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APPENDIX B

DETAILED COST ESTIMATES

APPENDIX B

DETAILED COST ESTIMATES

This appendix presents details of the treatment facility capital and operating costs. It also includes details on the transportation cost and disposal cost estimates.

B.1 TREATMENT FACILITY CAPITAL COSTS

The facility capital costs were prepared separately for the RH and CH processes. The RH process costs are detailed in Table B.1. The major assumptions, noted in the table footnotes, include the assumption that the installation cost for the remote equipment, which include the costs for adaptation for remote radioactive operations, is equal to the cost of the equipment itself. The volumes of the cells were estimated based on the size of the process equipment and the needed volume around the process equipment to allow operation and maintenance activities within the cells. The basic hot cell costs were estimated at $5,300/m^3 ($150/ft^3). An additional cost for galleries was included. The galleries were assumed to be two times the cell volume and were estimated to cost $880/m^3 ($25/ft^3). Therefore, the total cost for cell and gallery is $7,100/m^3 ($200/ft^3) based on the hot-cell volume. Indirect costs for engineering (15%), overheads and fees (35%), contract administration (3%) and contingency (25%) totaled 78% of the direct costs and are added to get the total shown in the last column for each of the processes. The indirect costs are also totaled for each of the alternatives.

The CH facility costs shown in Table B.2 were determined in the same manner as the RH facility costs described above. The major differences were that installation costs were taken to be one-half of the equipment costs, and that the processing room and an equivalent volume of support area were each excepted to cost $880/m^3 ($25/ft^3) of volume for a total cost of $1,800/m^3 ($50/ft^3) of

TABLE B.1. Remote-Handled Process Capital Costs (Common Support Areas Excluded)

Process	Equipment	Major Equipment: Equipment K$	Major Equipment: Installation K$[a]	Cell: Hot Cell Volume ft^{3}[b]	Cell: \$/ft^{3}[b]	Cell: Cell+Gal. K$	Direct Costs[c]	Indirect Costs[d]	Total Costs K$
ALTERNATIVE 1 - NO TREATMENT									
In-drum cementing	In-drum mixer	350	350	2,400	200	480	1,180	0.78	2,100
Drying	Band heater	5	5	300	200	60	70	0.78	125
Totals		355	355	2,700		540	1,250		2,225
ALTERNATIVE 2 - MRS REFERENCE									
Compaction	Drum compactor	74	74	4,000	200	800	948	0.78	1,687
In-drum cementing	In-drum mixer	350	350	2,700	200	540	1,240	0.78	2,207
Totals		424	424	6,700		1,340	2,188		3,895
ALTERNATIVE 3 - SUPERCOMPACTION									
Compaction	Compactor	74	74	4,000	200	800	948	0.78	1,687
Drying	Dryer	80	80	1,300	200	260	420	0.78	748
Supercompaction	Supercompactor	1,400	1,400	5,200	200	1,040	3,840	0.78	6,835
Totals		1,554	1,554	10,500		2,100	5,208		9,270
ALTERNATIVE 4 - MVR WITH DECONTAMINATION									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Decontamination	Decon System	100	100	2,200	200	440	640	0.78	1,139
Oxide Melting	Oxide Melter	1,000	1,000	4,500	200	900	2,900	0.78	5,162
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Size Reduction	Crusher	40	40	1,500	200	300	380	0.78	676
Totals		3,255	3,255	31,300		6,260	12,770		22,731
ALTERNATIVE 4A - MVR WITH DECONTAMINATION AND MELTING									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Decontamination	Decon System	100	100	2,200	200	440	640	0.78	1,139
Oxide Melting	Oxide Melter	1,000	1,000	4,500	200	900	2,900	0.78	5,162
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Total		3,215	3,215	29,800		5,960	12,390		22,054

TABLE B.1. (contd)

Process	Major Equipment: Equipment	Major Equipment: Equipment K$	Major Equipment: Installation K$[a]	Cell: Hot Cell Volume ft^3 [b]	Cell: $\$/ft^3$ [b]	Cell: Cell+Gal. K$	Direct Costs[c]	Indirect Costs[d]	Total Costs K$
ALTERNATIVE 4B - MVR WITH MELTING ONLY									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Oxide Melting	Oxide Melter	1,000	1,000	4,500	200	900	2,900	0.78	5,162
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Totals		3,115	3,115	27,600		5,520	11,750		20,915
ALTERNATIVE 4C - MVR WITH DECONTAMINATION AND CEMENTING									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Decontamination	Decon System	100	100	2,200	200	440	640	0.78	1,139
In-drum Cementing	In-drum Mixer	350	350	2,700	200	540	1,240	0.78	2,207
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Totals		2,565	2,565	28,000		5,600	10,730		19,099
ALTERNATIVE 4D - MVR WITH CEMENTING ONLY									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
In-drum Cementing	In-drum Mixer	350	350	2,700	200	540	1,240	0.78	2,207
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Totals		2,465	2,465	25,800		5,160	10,090		17,960
ALTERNATIVE 5 - CEMENTATION									
Shredding	Shredder	120	120	1,500	200	300	540	0.78	961
Grouting	2 I-D Grouters	75	75	3,800	200	760	910	0.78	1,620
Cementation	In-Drum Mixer	350	350	3,700	200	740	1,440	0.78	2,563
Totals		545	545	9,000		1,800	2,890		5,144

TABLE B.1. (contd)

Process	Major Equipment: Equipment	Major Equipment: Equipment K$	Major Equipment: Installation K$(a)	Cell: Hot Cell Volume ft3(b)	Cell: $/ft3(b)	Cell: Cell+Gal. K$	Direct Costs(c)	Indirect Costs(d)	Total Costs K$
ALTERNATIVE 6 - ARC PYROLYSIS AND MELTING									
Arc Melting	Arc Melter	1,000	1,000	15,000	200	3,000	5,000	0.78	8,900
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Size Reduction	Crusher	40	40	1,500	200	300	380	0.78	676
Totals		1,890	1,890	23,200		4,640	8,420		14,988
ALTERNATIVE 7 INTERMEDIATE QUALITY WASTE FORM									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Mixing/Grinding	Mixer/Grinder	50	50	3,000	200	600	700	0.78	1,246
Pressing	Warm Press	40	40	4,500	200	900	980	0.78	1,744
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Totals		2,205	2,205	30,600		6,120	10,530		18,743
ALTERNATIVE 8 - HIGHEST QUALITY WASTE FORM									
Separation System	Separator	200	200	4,500	200	900	1,300	0.78	2,314
Shredding	Shredder	65	65	1,500	200	300	430	0.78	765
Incineration	Incinerator	200	200	5,200	200	1,040	1,440	0.78	2,563
Off-Gas Treatment	O-G Treaters	850	850	6,700	200	1,340	3,040	0.78	5,411
Mixing/Grinding	Mixer/Grinder	50	50	3,000	200	600	700	0.78	1,246
Calcining	Calciner	100	100	1,500	200	300	500	0.78	890
Hot Pressing	2 Hot Presses	1,700	1,700	7,500	200	1,500	4,900	0.78	8,722
Metal Melting	Metal Melter	800	800	5,200	200	1,040	2,640	0.78	4,699
Size Reduction	Crushers	40	40	1,500	200	300	380	0.78	676
Totals		4,005	4,005	36,600		7,320	15,330		27,287

(a) Installation costs = 1.0 times equipment costs, which includes adaptation to remote radioactive operations.
(b) Cell costs = $150/ft^3; gallery volume is 2.0 times the cell volume at $25/cu ft; thus total cell + gallery cost is $200/ft^3 of cell volume.
(c) Direct costs = equipment costs, installation cost, plus hot cell and gallery costs.
(d) Indirect costs = general overheads and fee (35%) plus contract administration (3%) plus engineering (15%) for a subtotal of 53% of direct costs, plus contingency of 25% of direct costs for a grand total of 78% of direct costs.

TABLE B.2. CH Process Capital Costs (Common Support Areas Excluded)

Process	Major Equipment: Equipment	Major Equipment: Equipment K$	Instal'n K$	Process Room: Vol, ft^3	Process Room: $/$ft^3$	Process Room: Room+Gal. K$	Direct Costs; Room/Gal.+Eqp. + Instal'n K$	Indirect Costs Engg,Ohds,Fee, Conting. Ftr.	Total Costs K$
ALTERNATIVE 1 - NO TREATMENT									
(No Processes; Uses RH Cementation)		0	0	0	50	0	0	0.78	0
ALTERNATIVE 2 - MRS REFERENCE									
Compaction	Drum compactor	74	37	2,200	50	110	221	0.78	393
Size	Reduction Cutter	50	25	1,500	50	75	150	0.78	267
Cementation	In-Drum mixer	350	175	3,000	50	150	675	0.78	1,202
Totals		474	237	6,700		335	1,046		1,862
ALTERNATIVE 3 - SUPERCOMPACTION									
Compaction	Compactor	74	37	2,200	50	110	221	0.78	393
Drying	Dryer	5	3	300	50	15	23	0.78	40
Size Reduction	Cutter	50	25	1,500	50	75	150	0.78	267
Totals		129	65	4,000		200	394		700
ALTERNATIVE 4 - MAXIMUM VOLUME REDUCTION									
Separation System	Separator	100	50	3,000	50	150	300	0.78	534
Shredding	Shredder	65	33	1,500	50	75	173	0.78	307
Incineration	Incinerator	200	100	5,200	50	260	560	0.78	997
Off-Gas Treatment	O-G Treaters	850	425	6,000	50	300	1,575	0.78	2,804
Oxide Melting	Oxide Melter	1,000	500	4,500	50	225	1,725	0.78	3,071
Size Reduction	Crusher+Cutter	90	45	3,000	50	150	285	0.78	507
Totals		2,305	1,153	23,200		1,160	4,618		8,219
ALTERNATIVE 5 - CEMENTATION									
Shredding	Shredder	120	60	1,500	50	75	255	0.78	454
Size Reduction	Cutter	50	25	1,500	50	75	150	0.78	267
Cementation	In-Drum Mixer	350	175	3,000	50	150	675	0.78	1,202
Totals		520	260	6,000		300	1,080		1,922
ALTERNATIVE 6 - ARC PYROLYSIS AND MELTING									
Arc Melting	Arc Melter	1,000	500	12,000	50	600	2,100	0.78	3,738
Off-Gas Treatment	O-G Treaters	850	425	6,000	50	300	1,575	0.78	2,804
Size Reduction	Crusher+Cutter	90	45	3,000	50	150	285	0.78	507
Totals		1,940	970	21,000		1,050	3,960		7,049
ALTERNATIVE 7 INTERMEDIATE QUALITY WASTE FORM									
Separation System	Separator	100	50	3,000	50	150	300	0.78	534
Shredding	Shredder	65	33	1,500	50	75	173	0.78	307
Incineration	Incinerator	200	100	5,200	50	260	560	0.78	997
Off-Gas Treatment	O-G Treaters	850	425	6,000	50	300	1,575	0.78	2,804
Mixing/Grinding	Mixer/Grinder	50	25	2,200	50	110	185	0.78	329
Grouting	I-D Grouter	40	20	1,500	50	75	135	0.78	240
Size Reduction	Cutter	50	25	1,500	50	75	150	0.78	267
Totals		1,355	678	20,900		1,045	3,078		5,478
ALTERNATIVE 8 - HIGHEST QUALITY WASTE FORM									
Separation System	Separator	100	50	3,000	50	150	300	0.78	534
Shredding	Shredder	65	33	1,500	50	75	173	0.78	307
Incineration	Incinerator	200	100	3,500	50	175	475	0.78	846
Off-Gas Treatment	O-G Treaters	850	425	6,000	50	300	1,575	0.78	2,804
Calcining	Calciner	100	50	1,800	50	90	240	0.78	427
Hot Pressing	2 Hot Presses	1,500	750	7,500	50	375	2,625	0.78	4,673
Mixing/Grinding	Mixer/Grinder	50	25	3,000	50	150	225	0.78	401
Size Reduction	Cutter+Crusher	90	45	3,000	50	150	285	0.78	507
Totals		2,955	1,478	29,300		1,465	5,898		10,498
ALTERNATIVE 4A,B,C,D - MAXIMUM VOLUME REDUCTION									
Separation System	Separator	100	50	3,000	50	150	300	0.78	534

- Installation costs = 0.5 times equipment costs, which includes radioactive operations.
- Room costs = $25/$ft^3$; gallery volume is 1.0 times the cell volume; thus, total cell + gallery cost is $50/$ft^3$ of cell volume.
- Indirect costs = general overheads and fee (35%) plus contract (3%) plus engineering (15%) for a subtotal of 53% of direct costs, plus a contingency of 25% of direct costs for a grand total of 78% of

processing area. Direct costs are the sum of the equipment, installation, and the process room costs. The indirect costs are assessed at the same rate as for the RH wastes.

B.2 TREATMENT FACILITY OPERATING COSTS

The derivation of the annual operating costs for the alternatives is shown in Table B.3. The annual costs are comprised of three major types of costs: 1) cost of operation (i.e., manpower), 2) cost for containers, and 3) cost for assay, storage, and certification of the waste containers. Each of these costs is grouped in a segment of Table B.3 and then totaled. Basic operating costs are taken to be a fraction of the capital costs. The fraction was selected based on the degree of operator supervision required for the process. Simple processes such as cementing were taken to be 4% of the capital costs. Typically, 8% of the capital costs were used to estimate the annual operating costs. However, processes such as separation of wastes into components were taken as 10% of the capital costs.

The details of the cost for each of the various sizes of canisters are in Table B.3. Most of the canisters are stainless steel, but racks or packaging for the drums are taken to be mild steel. This cost is the most significant for the high volume waste forms. Optimization of the canister size was not considered in this study and should be considered further in additional analysis.

The cost for assay and certification is a major function of the number of containers, whereas the cost for the four months of interim storage is directly related to the volume of the waste form. The storage cost was based on our cost for hot-cell space and associated gallery space with a 11% efficiency of canister storage volume. This is necessary in part to allow sufficient space for heat removal by flowing air and access by an overhead crane.

B.3 TRANSPORTATION COSTS

The transportation cost estimates are shown in Table B.4. The table lists the can (canister or container) size, the number of cans per year, the capacity of the assumed shipping cask and cask shipping characteristics and costs. The

TABLE B.3. Annual Operating Costs

Process	Process Capital Cost, K$	Partial Fraction of Cap/yr	Process Operating Cost K$/yr	Package Description	New Containers No./yr	New Containers $/can	New Containers K$/yr	Reused Containers Containers/yr	Assay, Storage, Certify K$/yr	Total Operating Costs K$/yr
ALTERNATIVE 1 - NO TREATMENT										
RH Canisterizing	0	0.08	0	208-L drum, ss	2,193	300	658	284	1,239	
RH Drying	125	0.08	10	280-L can, ss	82	9,000	738		41	
RH Cementing	2,100	0.04	84	3000-L can, ss	419	7,000	2,933		210	
				5-pack rack, ms	496	300	149		0	
Total RH	2,225		94				4,478		1,489	7,013
CH Canisterizing	0	0.08	0	208-L drum, ss	667	300	200	1,092	440	
				303-L drum, ss	125	440	55		31	
				6-pack rack, ms	111	300	33		0	
Total CH	0						288		471	759
Total RH + CH	2,225		94				4,766		1,960	6,820
ALTERNATIVE 2 - MRS REFERENCE										
RH Compaction	1,687	0.08	135	208-L drum, ss	3,371	300	1,011	284	1,828	
RH Cementing	2,207	0.04	88	5-pack rack, ms	674	300	202		0	
Total RH	3,894		223				1,214		1,828	3,264
CH Cementing	1,202	0.04	48	208-L drum, ss	722	300	217	534	314	
CH Compaction	393	0.08	31	6-pack rack, ms	120	300	36		0	
CH Size Reduction	267	0.10	27							
Total CH	1,862		106				253		314	673
Total RH + CH	5,756		329				1,466		2,142	3,937
ALTERNATIVE 3 - SUPERCOMPACTION										
RH Drying	748	0.08	60	1280-L can, ss	129	9,000	1,161	284	207	
RH Compaction	1,687	0.08	135	5-pack rack, ms	57	300	17			
RH Supercompaction	6,835	0.08	547							
Total RH	9,270		742				1,178		207	2,126
CH Compaction	393	0.08	31	1280-L can, ss	47	9,000	423	346	98	
CH Drying	40	0.08	3	6-pack rack, ms	58	300	17			
CH Size Reduction	267	0.10	27				0			
Total CH	700		61				440		98	600
Total RH + CH	9,970		803				1,618		305	2,726

TABLE B.3. (contd)

Process	Process Capital Cost, K$	Partial Fraction of Cap/yr	Process Operating Cost K$/yr	Package Description	New Containers No./yr	New Containers $/can	New Containers K$/yr	Reused Containers Containers/yr	Assay, Storage, Certify K$/yr	Total Operating Costs K$/yr
ALTERNATIVE 4 - MAXIMUM WITH DECONTAMINATION										
RH Separation	2,314	0.12	278	208-L drum, LLW	269	300	81	0	135	
RH Shredding	765	0.08	61	333-L can, ss	354	4,700	1,664		177	
RH Incineration	2,563	0.10	256							
RH Off-Gas Treatment	5,411	0.08	433							
RH Decontamination	1,139	0.10	114							
RH Oxide Melting	5,162	0.08	413							
RH Metal Melting	4,699	0.08	376							
RH Size Reduction	676	0.10	68							
Total RH	22,729		1,998				1,745		312	4,054
CH Separation	534	0.12	64	208-L drum, LLW	152	300	46	0	38	
CH Shredding	307	0.08	25	333-L can, ss	166	4,700	780		42	
CH Incineration	997	0.10	100							
CH Off-Gas Treatment	2,804	0.08	224							
CH Oxide Melting	3,071	0.08	246							
CH Size Reduction	507	0.10	1							
Total CH	8,220		709				826		80	1,614
Total RH + CH	30,949		2,707				2,570		391	5,669
ALTERNATIVE 4A - MVR WITH DECONTAMINATION AND MELTING										
RH Separation	2,314	0.12	278	208-L drum, LLW	269	300	81	0	135	
RH Shredding	765	0.08	61	333-L can, ss	272	4,700	1,396		136	
RH Incineration	2,563	0.10	256	208-L drums, ss	0	300	2	284	142	
RH Off-Gas Treatment	5,411	0.08	433	5-pack rack, ms	57	300	17			
RH Decontamination	1,139	0.10	114							
RH Oxide Melting	5,162	0.08	413							
RH Metal Melting	4,699	0.08	376							
Total RH	22,053		1,931				1,376		413	3,719
CH Separation	534	0.12	64	208-L drum, LLW	152	300	46	0	38	
				333-L can, ss	5	4,700	24		1	
				208-L drum, ss	0	300	0	534	134	
				6-pack rack, ms	107	300	32		27	
Total CH	534		64				101		199	365
Total RH + CH	22,587		1,995				1,477		612	4,084

TABLE B.3. (contd)

Process	Process Capital Cost, K$	Partial Fraction of Cap/yr	Process Operating Cost K$/yr	Package Description	New Containers No./yr	New Containers $/can	New Containers K$/yr	Reused Containers Containers/yr	Assay, Storage, Certify K$/yr	Total Operating Costs K$/yr
ALTERNATIVE 4B - MVR WITH MELTING ONLY										
RH Separation	2,314	0.12	278	333-L can, ss	292	4,700	1,372		146	
RH Shredding	765	0.08	61	208-L DRUMS, SS	0	300	0	284	142	
RH Incineration	2,563	0.10	256	5-pack rack, ms	57	300	17			
RH Off-Gas Treatment	5,411	0.08	433							
RH Oxide Melting	5,162	0.08	413							
RH Metal Melting	4,699	0.08	376				0			
Total RH	20,914		1,817				1,389		288	3,494
CH Separation	534	0.12	64	333-L can, ss	16	4,700	75		24	
				208-L drum, ss	0	300	56	534	134	
				6-pack rack, ms	107	300	32		27	
Total CH	534		64				107		164	336
Total RH + CH	21,448		1,881				1,497		452	3,830
ALTERNATIVE 4C - MVR WITH DECONTAMINATION AND CEMENTING										
RH Separation	2,314	0.12	278	208-L DRUM, LLW	421	300	126	0	211	
RH Shredding	765	0.08	61	333-L can, ss	217	4,700	1,020		109	
RH Incineration	2,563	0.10	256	208-L drums, ss	428	300	134	284	356	
RH Off-Gas Treatment	5,411	0.08	433	5-pack rack, ms	142	300	43			
RH Decontamination	1,139	0.10	114							
RH Cementing	2,207	0.04	88							
RH Metal Melting	4,699	0.08	376							
Total RH	19,098		1,606				1,317		675	3,598
CH Separation	534	0.12	64	208-L drum, LLW	152	300	46	0	38	
				333-L can, ss	5	4,700	24		1	
				208-L drum, ss	0	300	0	534	134	
				6-pack rack, ms	107	300	32		27	
Total CH	534		64				101		199	365
Total RH + CH	19,632		1,670				1,418		874	3,963

TABLE B.3. (contd)

Process	Process Capital Cost, K$	Partial Fraction of Cap/yr	Process Operating Cost K$/yr	Package Description	New Containers No./yr	New Containers $/can	New Containers K$/yr	Reused Containers Containers/yr	Assay, Storage, Certify K$/yr	Total Operating Costs K$/yr
ALTERNATIVE 4D - MVR WITH CEMENTING ONLY										
RH Separation	2,314	0.12	278	333-L can, ss	238	4,700	1,119		119	
RH Shredding	765	0.08	61	208-L drums, ss	408	300	122	234	346	
RH Incineration	2,563	0.10	256	5-pack rack, ms	138	300	42			
RH Off-Gas Treatment	5,411	0.08	433							
RH Cementing	2,207	0.04	88							
RH Metal Melting	4,699	0.08	376							
Total RH	17,959		1,492				1,283		465	3,240
CH Separation	534	0.12	64	333-L can, ss	16	4,700	75		84	
				208-L drum, ss	0	300	86	534	134	
				6-pack rack, ms	107	300	32		27	
Total CH	534		64				107		164	336
Total RH + CH	18,493		1,556				1,390		629	3,575
ALTERNATIVE 5 - CEMENTATION										
RH Shredding	961	0.08	77	208-L drum, ss	3,962	300	1,189	234	2,123	
RH Grouting	1,620	0.04	65	5-pack rack, ms	849	300	255			
RH Cementation	2,563	0.04	103							
Total RH	5,144		244				1,443		2,123	3,911
CH Shredding	454	0.08	36	208-L drum, ss	1,016	300	305	534	388	
CH Size Reduction	267	0.10	27	6-pack rack, ms	153	300	78			
CH Cementation	1,202	0.04	48							
Total CH	1,923		111				382		388	891
Total RH + CH	7,067		355				1,826		2,511	4,691
ALTERNATIVE 6 - ARC PYROLYSIS AND MELTING										
RH Arc Melting	8,900	0.10	890	333-L can, ss	390	4,700	1,833	0	195	
RH Off-Gas Treatment	5,411	0.08	433							
RH Size Reduction	676	0.10	68							
Total RH	14,987		1,390				1,833		195	3,418
CH Arc Melting	3,738	0.10	374	333-L can, ss	213	4,700	1,001	0	53	
CH Off-Gas Treatment	2,804	0.10	280							
CH Size Reduction	507	0.10	51				0			
Total CH	7,049		705				1,001		53	1,759
Total RH + CH	22,036		2,095				2,834		248	5,178

TABLE B.3. (contd)

Process	Process Capital Cost, K$	Partial Fraction of Cap/yr	Process Operating Cost K$/yr	Package Description	New Containers No./yr	New Containers $/can	New Containers K$/yr	Reused Containers Containers/yr	Assay, Storage, Certify K$/yr	Total Operating Costs K$/yr
ALTERNATIVE 7 - INTERMEDIATE QUALITY WASTE FORM										
RH Separation	2,314	0.12	278	208-L drums, ss	0	300	0	284	142	
RH Shredding	765	0.08	61	333-L can, ss	245	4,700	1,152		123	
RH Incineration	2,563	0.10	256	1280-L can, ss	53	9,000	486		27	
RH Off-Gas Treatment	5,411	0.08	433	5-pack rack, ms	57	300	17			
RH Mixing/Grinding	1,246	0.10	125							
RH Pressing	1,744	0.08	140							
RH Metal Melting	4,699	0.08	376							
Total RH	18,742		1,668				1,655		292	3,614
CH Separation	534	0.12	64	208-L drum, ss	330	300	99	346	169	
CH Shredding	307	0.08	25	333-L can, ss	18	4,700	85		5	
CH Incineration	997	0.10	100	1280-L can, ss	6	9,000	54		2	
CH Off-Gas Treatment	2,804	0.08	224	6-pack rack, ms	113	300	34			
CH Mixing/Grinding	329	0.10	33							
CH Grouting	240	0.04	10							
CH Size Reduction	267	0.10	27				0			
Total CH	5,478		482				271		175	928
Total RH + CH	24,220		2,150				1,926		467	4,542
ALTERNATIVE 8 - HIGHEST QUALITY WASTE FORM										
RH Separation	2,314	0.12	278	333-L can, ss	487	4,700	2,289	0	244	
RH Shredding	765	0.08	61							
RH Incineration	2,563	0.10	256							
RH Off-Gas Treatment	5,411	0.08	433							
RH Mixing/Grinding	1,246	0.10	125							
RH Calcining	890	0.08	71							
RH Hot Pressing	8,722	0.08	698							
RH Metal Melting	4,699	0.08	376							
RH Size Reduction	676	0.10	68							
Total RH	27,286		7,365				2,289		244	4,8[illegible]
CH Separation	534	0.12	64	333-L can, ss	221	4,700	1,039	0	55	
CH Shredding	307	0.08	25							
CH Incineration	846	0.10	85							
CH Off-Gas Treatment	2,804	0.08	224							
CH Calcining	427	0.08	34							
CH Hot Pressing	4,673	0.08	374							
CH Mixing/Grinding	401	0.10	40							
CH Size Reduction	507	0.10	51							
Total CH	10,499		896				1,039		55	1,990
Total RH + CH	37,785		3,262				3,528		299	6,888

- Fraction of capital cost/yr as operating cost includes 2%/yr for capital improvements and replacements.
- Reused containers are those received from outside the MRS facility that receive no treatment in the MRS facility.
- The 5-pack and 6-pack racks are based on the total 208-L drums leaving the MRS facility.

TABLE B.4. Transportation Costs for RH, CH, and LLW Containers

Alternative No.	RH, CH, LLW	Can Size Lit.	Can Size Dia. x L, in.	Cans/yr	Cans/Cask	Casks/yr	Cask Days/yr	No of Casks	Cask Capital K$	Maint. K$/yr	Shipping K$/yr	Lifetime Costs, K$ Capital	Lifetime Costs, K$ Maint.	Lifetime Costs, K$ Shipping	Lifetime Costs, K$ Shipping + Maint.	Total
1	RH	208	24 x 36	2,477	20	123.9	2,835	9.4	22,500	1,125	5,474	45,000	26,213	127,548	153,761	198,761
		1280	24 x 180	82	4	20.5	469	1.6	5,000	250	906	10,000	5,925	21,112	26,937	36,937
		3000	36 x 180	419	1	419.0	9,591	32.0	80,000	4,000	18,520	160,000	93,200	431,511	524,711	684,711
Total RH						563.4	12,895	43.0	107,500	5,375	24,900	215,000	125,238	580,172	705,499	920,409
	CH	208	24 x 36	1,759	36	48.9	1,118	3.7	3,200	300	658	6,400	6,990	15,336	22,326	28,726
		303	29 x 32	125	36	3.5	79	0.3	800	75	47	1,600	1,743	1,090	2,837	4,437
Total CH						52.3	1,989	4.0	4,000	375	705	8,000	8,738	16,426	25,164	33,164
Total RH + CH									111,500	5,750	25,605	223,000	133,975	596,598	730,573	953,573
including security											26,331			613,520	747,495	970,495
2	RH	208	24 x 36	3,655	20	182.8	4,183	13.9	35,000	1,750	8,078	70,000	40,775	188,207	228,982	316,833
	CH	208	24 x 36	1,256	36	34.9	799	2.7	2,400	225	470	4,800	5,243	10,951	16,193	20,993
Total RH + CH						217.6	4,982	16.6	37,400	1,975	8,548	74,800	46,018	199,159	245,175	319,975
including security											8,794			204,904	250,922	325,722
3	RH	208	24 x 36	454	20	22.7	520	1.7	5,000	250	1,003	10,000	5,825	23,378	29,203	39,203
		1280	24 x 180	129	4	32.3	738	2.5	7,000	375	1,425	15,000	8,738	33,213	41,950	56,950
Total RH						55.0	1,258	4.2	12,500	625	2,429	25,000	14,563	56,591	71,153	96,153
	CH	208	24 x 36	554	36	15.4	352	1.2	1,600	150	207	3,200	3,495	4,830	8,325	11,525
		1280	24 x 180	33	4	8.3	189	0.6	800	75	111	1,600	1,748	2,589	4,337	5,937
Total CH						23.6	541	1.8	2,400	225	318	4,800	5,243	7,420	12,662	17,462
Total RH + CH						86.0	1,799	6.0	14,900	850	2,747	29,800	19,805	64,010	83,815	113,615
including security											2,829			65,927	85,732	115,532
4	RH	333	12 x 180	354	9	39.3	900	3.0	7,500	375	1,739	15,000	8,738	40,508	49,245	64,245
	CH	333	12 x 180	165	15	11.0	252	0.8	800	75	149	1,600	1,748	3,453	5,200	6,800
Total RH + CH						50.3	1,152	3.8	8,300	450	1,887	16,600	10,485	43,960	54,445	71,045
including security											1,942			45,247	55,732	72,332
	CH-LLW	208	24 x 36	421	70	6.0	--	--	--	--	486	--	--	11,324	11,324	11,324
Total RH + CH + LLW																83,656
4A	RH	208	24 x 36	284	20	14.2	335	1.1	5,000	250	628	10,000	5,825	14,624	20,449	30,449
	RH	333	12 x 180	272	9	30.2	692	2.3	7,500	375	1,336	15,000	8,738	31,125	39,862	54,862
Total RH						44.4	1,017	3.4	12,500	625	1,963	25,000	14,563	45,749	60,311	85,311
	CH	208	24 x 36	534	36	14.8	340	1.1	1,600	150	200	3,200	3,495	4,656	8,151	11,351
		333	12 x 180	5	15	0.3	8	0.0	800	75	4	1,600	1,748	105	1,852	3,452
Total CH						15.2	347	1.2	2,400	225	204	4,800	5,243	4,760	10,003	14,803
Total RH + CH						59.6	1,364	4.5	14,900	850	2,168	29,800	19,805	50,509	70,314	100,114
including security											2,232			52,002	71,807	101,607
	CH-LLW	208	24 x 36	503	70	6.0	--	--	--	--	486	--	--	11,324	11,324	11,324
Total RH + CH + LLW																112,931

TABLE B.4. (contd)

Alternative No.	RH, CH, LLW	Can Size Lit.	Can Size Dia. x L, in.	Cans/ yr	Cans/ Cask	Casks/ yr	Cask Days/ yr	No of Casks	Cask Capital K$	Maint. K$/yr	Shipping K$/yr	Lifetime Costs, K$ Capital	Maint.	Shipping	Shipping + Maint.	Total
4B	RH	208	24 x 36	284	20	14.2	325	1.1	5,000	250	628	10,000	5,825	14,624	20,449	30,449
	RH	333	12 x 180	292	9	32.4	743	2.5	7,500	375	1,434	15,000	8,738	33,413	42,151	57,151
Total RH						46.6	1,068	3.6	12,500	625	2,062	25,000	14,563	48,037	62,600	87,600
	CH	208	24 x 36	534	36	14.8	340	1.1	1,600	150	200	3,200	3,495	4,656	8,151	11,351
		333	12 x 180	16	15	1.1	24	0.1	800	75	14	1,600	1,748	335	2,082	3,682
Total CH						15.9	364	1.2	2,400	225	214	4,800	5,243	4,991	10,233	15,033
Total RH + CH						62.5	1,432	4.8	14,900	850	2,276	29,800	19,805	53,028	72,833	102,633
including security											2,343			54,595	74,400	104,200
4C	RH	208	24 x 36	712	20	35.6	815	2.7	7,500	375	1,574	15,000	8,738	36,663	45,401	60,401
	RH	333	12 x 180	217	9	24.1	552	1.8	5,000	250	1,066	10,000	5,825	24,831	30,656	40,656
Total RH						59.7	1,367	4.6	12,500	625	2,639	25,000	14,563	61,494	76,057	101,057
	CH	208	24 x 36	534	36	14.8	340	1.1	1,600	150	200	3,200	3,495	4,656	8,151	11,351
		333	12 x 180	5	15	0.3	8	0.0	800	75	4	1,600	1,748	105	1,852	3,452
Total CH						15.2	347	1.2	2,400	225	204	4,800	5,243	4,760	10,003	14,803
Total RH + CH						74.9	1,714	5.7	14,900	850	2,844	29,800	19,805	66,255	86,060	115,860
including security											2,926			68,186	97,991	117,791
	CH-LLW	208	24 x 36	421	70	6.0	--	--	--	--	486	--	--	11,324	11,324	11,324
Total RH + CH + LLW																129,115
4D	RH	208	24 x 36	692	20	34.6	792	2.6	7,500	375	1,529	15,000	8,728	35,663	44,371	59,371
	RH	333	12 x 180	238	9	26.4	605	2.0	5,000	250	1,169	10,000	5,825	27,234	33,059	43,059
Total RH						61.0	1,397	4.7	12,500	625	2,698	25,000	14,563	62,867	77,430	102,430
	CH	208	24 x 36	534	36	14.8	340	1.1	1,600	150	200	3,200	3,495	4,656	8,151	11,351
		333	12 x 180	16	15	1.1	24	0.1	800	75	14	1,600	1,748	335	2,082	3,682
Total CH						15.9	364	1.2	2,400	225	214	4,800	5,243	4,991	10,233	15,033
Total RH + CH						76.9	1,761	5.9	14,900	850	2,912	29,800	19,805	57,858	87,663	117,463
including security											2,997			69,838	89,643	119,443
5	RH	208	24 x 36	4,246	20	212.3	4,860	16.2	42,500	2,125	9,384	85,000	49,513	218,639	268,152	353,152
	CH	208	24 x 36	1,550	36	43.1	986	3.3	3,200	300	580	6,400	6,990	13,514	20,504	26,904
Total RH + CH						255.4	5,845	19.5	45,700	2,425	9,964	91,400	56,503	232,153	288,656	380,056
including security											10,252			238,865	295,368	386,768

TABLE B.4. (contd)

Alternative No.	RH, Ch, LLW	Can Size Lit.	Can Size Dia. x L, in.	Cans/ yr	Cans/ Cask	Casks/ yr	Cask Days/ yr	No of Casks	Cask Capital K$	Maint. K$/yr	Shipping K$/yr	Lifetime Costs, K$ Capital	Maint.	Shipping	Shipping + Maint.	Total
6	RH	333	12 x 180	390	9	43.3	992	3.3	10,000	500	1,915	20,000	11,650	44,627	56,277	76,277
	CH	333	12 x 180	213	15	14.2	325	1.1	1,600	150	191	3,200	3,495	4,457	7,952	11,152
Total RH + CH						57.5	1,317	4.4	11,600	650	2,107	23,200	15,145	49,084	64,229	87,429
including security											2,169			50,532	65,677	88,877
7	RH	208	24 x 36	284	20	14.2	325	1.1	5,000	250	628	10,000	5,825	14,624	20,449	30,449
		333	12 x 180	256	9	27.2	623	2.1	7,500	375	1,203	15,000	8,738	28,035	36,773	51,773
		1280	24 x 180	54	4	13.5	309	1.0	2,500	125	597	5,000	2,913	13,903	16,816	21,816
Total RH						54.9	1,257	4.2	15,000	750	2,428	30,000	17,475	56,562	74,037	104,037
	CH	208	24 x 36	676	36	18.8	430	1.4	1,600	150	253	3,200	3,495	5,894	9,389	12,589
		333	12 x 180	18	15	1.2	27	0.1	800	75	16	1,600	1,748	377	2,124	3,724
		1280	24 x 180	6	4	1.5	34	0.1	included with numbers in prior row							
Total CH						21.5	492	1.6	2,400	225	269	4,800	5,243	6,271	11,513	16,313
Total RH + CH						76.4	1,749	5.8	17,400	975	2,697	34,800	22,718	62,833	85,550	120,359
including security											2,778			64,718	87,435	122,235
8	RH	333	12 x 180	487	9	54.1	1,239	4.1	12,500	625	2,392	25,000	14,563	55,727	70,289	95,289
	CH	333	12 x 180	221	15	14.7	337	1.1	1,600	150	198	3,200	3,495	4,624	8,119	11,319
Total RH + CH						68.8	1,576	5.3	14,100	775	2,590	28,200	18,058	60,351	78,409	106,609
including security											2,666			62,116	80,174	108,374

- All RH-TRUW shipments are in 100-t casks in 5-car dedicated trains; CH-TRUW is shipped in 2 TRUPACTS per rail car.
- TRUW shipment costs are based on DOE/RW-0035, Volume 2, Appendix F; LLW costs are based on PNL-4064, with costs escalated to 1985.
- Cans/cask or TRUPACT are based primarily on DOE/RW-0035; non-208-L drums/TRUPACT are estimated by the authors.
- Shipments/yr = cans/yr divided by cans/load.
- Cask days/yr = shipments/yr times 22.89, per DOE/RW-0035, Volume 2, Appendix F, for one-way trip = 2000 miles.
- Number of casks = cask days/yr divided by 300 days/yr operation.
- Cask capital cost = number of casks (rounded upward to nearest whole number) times $M 2.5 per rail cask and $M 0.8/TRUPACT.
- Cask maintenance cost = number of casks/yr times $M 0.125/yr; for TRUPACT the factor is $M 0.075/yr.
- Rail cask shipping costs = 44.2 times shipments/yr for 2000 miles each way; for TRUPACT the factor is 13.47.
- Lifetime capital costs assume cask/TRUPACT life is 15 years; thus, each cask/TRUPACT is replaced once in the facility lifetime.
- Lifetime maintenance and shipping costs are 23.3 (facility operating years) times the annual costs.
- LLW shipping costs are $2.69/mile for the 300 miles assumed, per PNL-4064.
- Security costs are per DOE/RW-0035; K$/yr = [RH casks/yr + CH casks/yr/2](6,159.79)(1/5,000), or [ ](1.2320).

lifetime costs shown in the table are estimated from the annual costs. The major assumptions and basis of the calculations are shown as footnotes in the table.

B.4 DISPOSAL COSTS

The disposal costs were estimated from an equation fit to a previous set of data (Ross et al. 1985). Several different equations were tested and the one found best was:

$$\text{costs} = a\sqrt{\text{vol}} + b(\text{vol})$$

The form of the equation is appropriate because at low volumes the costs increase rapidly due to the predominance of capital and fixed costs, whereas at high volumes, the costs should be near linear with waste volume as costs become more controlled by operations. The a and b parameters determined from the regression analysis were respectively 8.16×10^6 and 1.54×10^3 for RH waste, and 2.13×10^6 and -1.32×10^4 for the CH wastes when the volumes are expressed in cubic meters for 70,000 MTU. These costs were then escalated to 1985 dollars by a factor of 1.042.

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