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

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PRELIMINARY ANALYSIS OF TREATMENT STRATEGIES FOR TRANSURANIC WASTES FROM REPROCESSING PLANTS

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We would also like to acknowledge the fine support provided hy Susan King and Donna Kuick in editing and coordinating the publication of the drafts and final document. The preparation of this report required many hours of extra effort on their part and on the part of Marlene Hale's word processing team. We would also like to thank those who took time from their husy schedules to review drafts of the report.

ABSTRACT

This document provides a comparison of six treatment options for transuranic wastes (TRUW) resulting from the reprocessing of commercial spent fuel. Projected transuranic waste streams from the Barnwell Nuclear Fuel Plant (BNFP), the reference fuel reprocessing plant in this report, were grouped into the five categories of hulls and hardware, failed equipment, filters, flourinator solids, and general process trash (GPT) and sample and analytical cell (SAC) wastes.

Six potential treatment options were selected for the five categories of waste. These options represent six basic treatment objectives: 1) no treatment, 2) minimum treatment (compaction), 3) minimum number of processes and products (cementing or grouting), 4) maximum volume reduction without decontamination (melting, incinerating, hot pressing), 5) maximum volume reduction with decontamination (decontamination, treatment of residues), and 6) noncombustible waste forms (melting, incinerating, cementing). Schemes for treatment of each waste type were selected and developed for each treatment option and each type of waste. From these schemes, transuranic waste volumes were found to vary from 1 m^3/MTU for no treatment to as low as 0.02 m^3/MTU.

Based on conceptual design requirements, life-cycle costs were estimated for treatment plus on-site storage, transportation, and disposal of both high-level and transuranic wastes (and incremental low-level wastes) from 70,000 MTU. For all treatment cases (Options 2 through 6), the additional costs for treatment were more than compensated for by the reduced cost of transportation and disposal in amounts ranging from $0.1 billion to $1.7 billion (in 1983 undiscounted dollars).

The study concludes that extensive treatment is warranted from both cost and waste form characteristics considerations, and that the characteristics of most of the processing systems used are acceptable. The study recommends that additional combinations of treatment methods or strategies be evaluated and that in the interim, melting, incineration, and cementing be further developed for commercial TRUW.

GLOSSARY

AGNS	- Allied-General Nuclear Services
ALARA	- as low as reasonably achievable
ASTM	- American Society for Testing and Materials
BNFP	- Barnwell Nuclear Fuel Plant
BWIP	- Basalt Waste Isolation Program
CH	- contact handled
CH TRUW	- contact-handled transuranic waste
DOE	- U.S. Department of Energy
DOT	- U.S. Department of Transportation
EPA	- U.S. Environmental Protection Agency
GPT	- general process trash
H&H	- hulls and hardware
HEPA	- high-efficiency particulate air (filter)
HLLW	- high-level liquid waste
HLW	- high-level waste
i.d.	- inside diameter
ILLW	- intermediate-level liquid waste
ILW	- intermediate-level waste
INEL	- Idaho National Engineering Laboratory
LLW	- low-level waste
MOX	- mixed oxide (fuel)
MT	- metric ton
MTU	- metric tons uranium
MWD/MTU	- megawatt days per metric tons uranium
nCi/g	- nanocuries per gram
NRC	- U.S. Nuclear Regulatory Commission
NWTP	- Nuclear Waste Treatment Program
OCRWM	- Office of Civilian Radioactive Waste Management
PNL	- Pacific Northwest Laboratory
PVC	- polyvinyl chloride
R&D	- research and development
RECON	- Repository Economics Model

RH	- remote handled
RH TRUW	- remote-handled transuranic waste
SAC	- sample and analytical cell (waste)
TRU	- transuranic
TRUW	- transuranic waste
TRUPACT	- Transuranic Package Transporter
WAC	- Waste Acceptance Criteria
WIPP	- Waste Isolation Pilot Plant

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FIGURES

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1.0 INTRODUCTION

Transuranic waste (TRUW) will be generated during the spent fuel reprocessing and fuel refabrication steps of the nuclear fuel cycle, in which fissionable uranium and plutonium are recovered and recycled for beneficial use. Transuranic wastes can also be generated in the handling and storage of spent fuel, particularly if any of the fuel cladding is failed. Defense activities in the processing of plutonium for weapons have generated TRU wastes as well.

Transuranic waste consists of unusable material contaminated with transuranic radionuclides in concentrations greater than 100 nCi/g of waste. Transuranic waste can originate in a wide variety of forms. Original commercial TRUW forms can include failed equipment, fuel cladding and hardware, ventilation filters, process solids, and general process and laboratory operational scrap (which includes paper, rags, wood, glass, metals, plastics, and ceramics).[(a)] The final type of disposal of commercial TRU wastes has not been determined, but it is expected to be deep geologic disposal with commercial HLW. In this case the TRU wastes, plus the other engineered barriers in the repository, may be required to meet the U.S. Nuclear Regulatory Commission (NRC) requirement for control of the annual fractional release rate of radionuclides to less than 10^{-5}. It is likely that most of the wastes will need some type of treatment to meet this limit. Tests of the selected products will be needed to confirm their acceptability.

Because of the possible need for a number of treatment processes for the wide variety of original TRUW forms, it is appropriate to study the potential treatment strategies and their impacts on the waste management system. Fuel reprocessing will generate TRUW that includes the full range of original waste forms. These wastes will also have a broad range of beta-gamma radioactivity levels, which will require that significant amounts be shielded and remotely handled. Mixed oxide (MOX) fuel refabrication will generate TRUW with a much

(a) Original TRUW forms can also include organic and inorganic liquids, and process sludges, but these are assumed in this study to be intermediate-level wastes.

narrower range of forms and with generally little beta-gamma radioactivity content. It was thus believed that an analysis of potential waste treatment strategies for TRUW from fuel reprocessing of spent fuel would be broad enough to cover most of the waste management concerns for both fuel cycle steps.

The study documented in this report was performed 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). The study was also conducted in collaboration with related work being carried out for DOE's Office of Civilian Radioactive Waste Management (OCRWM) in the Waste Management Systems Studies at PNL (McKee et al. 1984). The objective of this study is to provide analyses of various TRUW treatment options at a fuel reprocessing plant and the cost impacts of these options on the total waste management system. Six options with differing fundamental objectives were studied. The results of the study will provide DOE with a basis for decisions concerning the scope, schedule, and budget for the transuranic waste studies of the Nuclear Waste Treatment Program. This study represents the first step in the development of an integrated TRUW treatment technology (discussed in Section 3).

This report is divided into 10 sections. Section 2 is a summary of the results and conclusions. Section 3 describes the plans for development of overall TRUW treatment technology and the approach for this study, and Section 4 provides the overall bases for the study. The characterization of TRUW streams is given in Section 5. Section 6 presents the definition of the six basic treatment options evaluated, the logic for their derivation, and initial screening. Section 7 presents the detailed process descriptions of the six basic treatment options, and Section 8 presents an evaluation of waste management costs. An overall evaluation and a comparison of results are given in Section 9, and conclusions and recommendations are provided in Section 10. References and supporting appendixes follow.

1.1 REFERENCE

McKee, R. W., L. L. Clark, P. M. Daling, J. F. Nesbitt, and J. L. Swanson. 1984. "Economic Analysis of Waste Management System Alternatives for Reprocessing Wastes." Waste Management 1984, pp. 383-393. University of Arizona, Tucson.

2.0 SUMMARY

Transuranic waste (TRUW) treatment strategies have been prepared based on the treatment, transportation, and disposal of high-level waste (HLW) and TRUW from a reference reprocessing plant. The Barnwell Nuclear Fuel Plant (BNFP) was the reference facility selected for this study. The potential waste streams from this facility have been well characterized and reviewed previously (Darr 1983). The streams were grouped into the five categories of hulls and hardware, failed equipment, filters, fluorinator solids, and general process trash (GPT) plus sample and analytical cell (SAC) wastes. These wastes are composed of a wide variety of materials including metal, cellulose, plastics, and rubber.

Six potential treatment options, including the option of no treatment, were selected for the five categories of waste and are summarized in Table 2.1. These options were selected to represent different objectives and potential methods for obtaining them. Reducing waste volumes was found in all cases to reduce waste management system costs. Several of the options consider different ways to reduce waste volumes (e.g., compaction, incineration, melting, and decontamination). The ability of each of the options to reduce the volume of waste is shown in Table 2.2. The options demonstrate that it is possible to reduce the TRUW volumes by a factor greater than 10, using selected processing methods. As shown, Option 5 (decontamination) includes the incorporation of some TRUW into the HLW stream and the removal of TRU contamination to convert some TRUW to low-level waste (LLW). Decontamination has the potential to provide the greatest reduction in the volumes of TRUW plus HLW, but it also generates a large volume of LLW.

Since some of the TRUW is converted to HLW in one of the treatment options evaluated (Option 5), and since the disposal costs for HLW and TRUW in the same deep geologic repository are interdependent, the total costs for both HLW and TRUW are considered in this evaluation. Incremental costs for LLW resulting from TRUW treatments are also included.

The calculated costs for treatment, transportation, and disposal of the treated TRUW (and incremental LLW) from reprocessing 70,000 MTU of spent fuel

TABLE 2.1. Summary of the Six TRUW Treatment Options[a]

Option	Title	Objective	Primary Treatments
1	No treatment	No treatment of wastes	Assay to certify TRU content and whether contact or remote handled
2	Minimum treatment	Reduce volume with simple technology	All wastes are mechanically compacted to reduce volume
3	Minimum number of processes and products	Treat wastes in similar manner to produce one type of simple waste form	All wastes are mixed with cement or grouted
4	Maximum volume reduction without decontamination	Treat wastes to produce minimum final waste volumes	Metals are melted, cellulose combustibles are incinerated, rubber and plastics are hot pressed, and residues are melted
5	Maximum volume reduction with decontamination	Decontaminate TRUW to produce LLW	Wastes are decontaminated; residue is combined with HLW or treated separately[b]
6	Noncombustible waste forms	Reduce volume and eliminate combustibles	Metals are melted, combustibles are incinerated, and residues are cemented

(a) HLW is treated by vitrification in all options. A more detailed description of TRUW treatments is given in Table 7.1.

(b) Suboption 5A vitrifies decontamination solutions with HLW glass, while Suboption 5B dries the decontamination solution and hot presses the solids from hull treatment.

TABLE 2.2. Annual Volumes of Treated Wastes from a 1,500 MTU/yr Reprocessing Plant for the Six TRUW Treatment Options

Option	Contact-Handled TRUW, m^3	Remote-Handled TRUW, m^3	Increase in HLW, m^3	Increase in LLW, m^3	Total TRUW and HLW, m^3
1	480	980	--	--	1,460
2	55	300	--	--	355
3	89	860	--	--	949
4	7	110	--	--	117
5A	4	14	79	530	97
5B	4	23	4	530	31
6	28	110	--	57	138

are shown in Table 2.3. All other treatment options have costs lower than those for Option 1 (no treatment), and these incrementally lower costs range from $0.2 billion for Option 3 (minimum number of processes and products) to $2.0 billion for Option 6 (noncombustible waste forms). The increase in treatment costs for Options 2 through 6 over those for Option 1 are more than compensated for by significant reductions in transportation and disposal costs. It should he added that the largest contribution to disposal costs in Suhoptions 5A and 5B (maximum volume reduction with decontamination) comes from incremental LLW disposal costs.

Table 2.4 includes the same costs given in Table 2.3, with the addition of HLW management costs. These costs show the total costs for the system defined in this study. (Treatment R&D and decommissioning costs and repository selection and development costs are excluded in this study.) Again, all the other treatment options have a lower overall cost than Option 1 (no treatment). A significant reduction in transportation and disposal costs can be noted by comparing the costs for Options 2 through 6 with the costs for Option 1. These cost differences demonstrate the major impact of volume reduction on overall system costs.

Comparison of Tables 2.3 and 2.4 shows various reductions in the cost incentives for the treatment options (Option 2 through 6) when incremental HLW

TABLE 2.3. Costs for Treatment, Transportation, and Disposal of TRUW and Incremental LLW from 70,000 MTU of Reprocessed Spent Fuel (undiscounted 1983 $ billions)[a]

Option	Treatment	Transportation	Disposal	Total	Cost Reduction Relative to Option 1
1	1.2	1.4	2.2	4.8	--
2	1.5	0.3	1.4	3.2	1.6
3	1.5	1.2	1.9	4.6	0.2
4	2.2	0.1	0.6	2.9	1.9
5A[b]	2.6	0.05	0.7	3.4	1.4
5B[b]	3.0	0.06	0.7	3.8	1.0
6[b]	2.2	0.1	0.6	2.9	2.0

(a) Treatment costs include amortized capital and operating costs; transportation costs assume commercial general freight costs plus cask leasing plus security costs; disposal costs include construction and operation costs of a basalt repository for TRUW and HLW, and commercial burial ground charges for LLW disposal.

(b) Includes incremental costs for LLW treatment, transportation, and disposal, which are incurred in this option.

management costs are added to derive the system costs. However, these system cost reductions are still significant in some cases (Options 2, 4, and 6), ranging from $0.1 billion in Option 3 (minimum number of processes and products) to $1.7 billion in Option 6 (noncombustible waste forms). Option 2 (minimum treatment) has a cost incentive of $1.5 billion and Option 4 (maximum volume reduction without decontamination) has a cost incentive of $1.6 billion.

The strategy analysis in this study also took into consideration the requirements for waste forms and canisters and waste processing characteristics. The waste form considerations included recognition that the requirements being developed include those for defense TRUW to be sent to the Waste Isolation Pilot Plant (WIPP), the Class C LLW requirements in 10 CFR 61 (U.S. NRC 1984a), and the HLW and TRUW requirements in 10 CFR 60 (U.S. NRC 1984b) for geologic disposal. Since the detailed disposal method for TRUW has not yet been established and detailed characterization data for the respective waste

TABLE 2.4. Costs for Treatment, Transportation, and Disposal of HLW, TRUW, and Incremental LLW from 70,000 MTU of Reprocessed Spent Fuel (undiscounted 1983 $ billions)[a]

Option	Treatment	Transportation	Disposal	Total	Cost Reduction Relative to Option 1
1	3.7	1.7	4.9	10.3	--
2	4.0	0.6	4.2	8.8	1.5
3	4.0	1.5	4.6	10.2	0.1
4	4.7	0.4	3.6	8.7	1.6
5A[b]	5.5	0.6	3.9	10.0	0.3
5B[b]	5.5	0.4	3.9	9.8	0.5
6[b]	4.7	0.4	3.6	8.6	1.7

(a) Treatment costs include amortized capital and operating costs; transportation costs assume commercial general freight costs plus cask leasing plus security costs; disposal costs include construction and operation of a basalt repository for TRUW and HLW, and commercial burial ground charges for LLW disposal.
(b) Includes incremental costs for LLW treatment, transportation, and disposal, which are incurred in this option.

forms have not been obtained, the acceptability of waste forms cannot be fully judged. However, it seems likely that waste forms will be required to provide some immobilization of particulates, high chemical durability, and elimination of any pyrophoric and combustible materials. In comparing the probable waste form characteristics in the treatment options with these potential requirements, Option 6 was judged to be the most likely to be acceptable under the anticipated requirements. Options 3, 4, and 5 were considered likely to be generally acceptable. However, there are concerns about the particulate, potentially pyrophoric, and combustible materials present in Options 1 and 2. The relative ranking of the process options relative to waste form requirements is given in column 3 of Table 2.5.

Processing characteristics such as operational safety, process complexity, technology status, and process flexibility were evaluated qualitatively by the

authors. The aggregate results are shown in column 4 of Table 2.5. The simpler treatment options (Options 1 and 2) possess the more favorable processing characteristics. Options 4 and 5 were judged to have the least favorable processing characteristics of the six options, and Options 3 and 6 were judged to be intermediate.

By combining the rankings of the options studied relative to waste form characteristics and processing characteristics with those for system economics (given in Column 2 of Table 2.5 and based on the costs in Table 2.4), an approximate overall ranking is given in Column 5 of Table 2.5. This overall ranking, obtained by addition of the values in Columns 2, 3, and 4, assumes that the values are equally weighted. It should be noted that processing would have to be given greater weight than the combined categories of system economics and waste form characteristics to change the results.

This simple comparison provides some valuable insights. The ranking indicates that Option 6 is the most favorable and Options 1 and 5 are the least favorable. Although waste form requirements may not be known currently, they may well provide "go/no-go" bases for evaluating the waste forms for the

TABLE 2.5. Summary Ranking of the Selected TRUW Treatment Options

Option	System Economics[a]	Waste Form Characteristics[a]	Processing Characteristics[a]	Approximate Overall Ranking[b]
1	6	6	1	13
2	3	5	2	10
3	5	4	3	12
4	2	2	5	9
5	4	3	6	13
6	1	1	4	6

(a) Ranking of from 1 (most favorable) to 6 (least favorable of the group).
(b) Approximate overall ranking is by addition of the prior three values for each option, with the lower numbers being the most favorable.

various strategies. In that case, the options with the poorer waste form ranking (higher numbers) could well be eliminated, and the better waste forms would have a better chance of meeting the requirements. The more extensive treatment options (Options 4, 5, and 6) are ranked the most desirable in the waste form category, with the ranking for Option 6 as the most favorable. Option 6 also presents the most favorable system economics and has the most favorable processing characteristics of the more extensive treatment options (Options 4, 5, and 6). Option 5 appears to be the least favorable of the more extensive treatment options.

Based on these evaluations, it appears that Option 6 potentially may have the most favorable characteristics of all the options studied. Option 4 appears to have the next most favorable characteristics of the more extensive treatment options, and ranks least favorably only in processing characteristics.

Implementation of Options 1, 2, and 3 would require little or no R&D, but these options rank relatively poorly. Option 6 appears to offer significant potential advantages over the other options, and R&D for this option appears to be warranted. Next in line for potential improvements in the waste management system is Option 4.

Other options could be constructed for further evaluation based on the selection and evaluation of specific treatments from the six options presented here. For example, a simplified decontamination option that would decontaminate the hulls and leave the remaining wastes to be treated by other methods could be examined. Hulls are of special interest because they are the largest volume stream and have high radiation levels.

In constructing the treatment options evaluated in this study, it was recognized that high-efficiency particulate air (HEPA) filters comprise a relatively large volume of waste that is apparently difficult to treat. It should also be recognized that the treatment of polyvinyl chloride (PVC) plastics presents process difficulties, and that the development or utilization of alternative materials (to eliminate PVC and halogen-containing materials from TRUW) would simplify TRUW incineration.

This study demonstrated that there are significant opportunities for combining wastes for treatment. Therefore, future R&D should consider all the waste streams, as we have done in this study. Metal melting, incineration of combustibles, and cementing of residues are candidates for further development based on the six basic options studied. These processes have the capabilities to reduce waste volume and waste management system costs, to handle a large variety of wastes, and to produce good quality waste forms.

2.1 REFERENCES

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

U.S. Nuclear Regulatory Commission. 1984a. Code of Federal Regulations, Title 10, Energy; Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, Final Rule. U.S. Federal Register, Vol. 47, December 27, 1982 (Effective January 26, 1983), p. 57463. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984b. Code of Federal Regulations, Title 10, Energy; Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories (Subpart E, Technical Criteria). Final Rule, U.S. Federal Register, Vol. 48, No. 120, June 21, 1983, pp. 28194-28229. U.S. NRC, Washington, D.C.

3.0 STUDY APPROACH

This study represents the first step in the development of an integrated TRUW treatment technology, as illustrated in Figure 3.1. Following this strategy analysis are three activities: 1) more detailed selection of processes

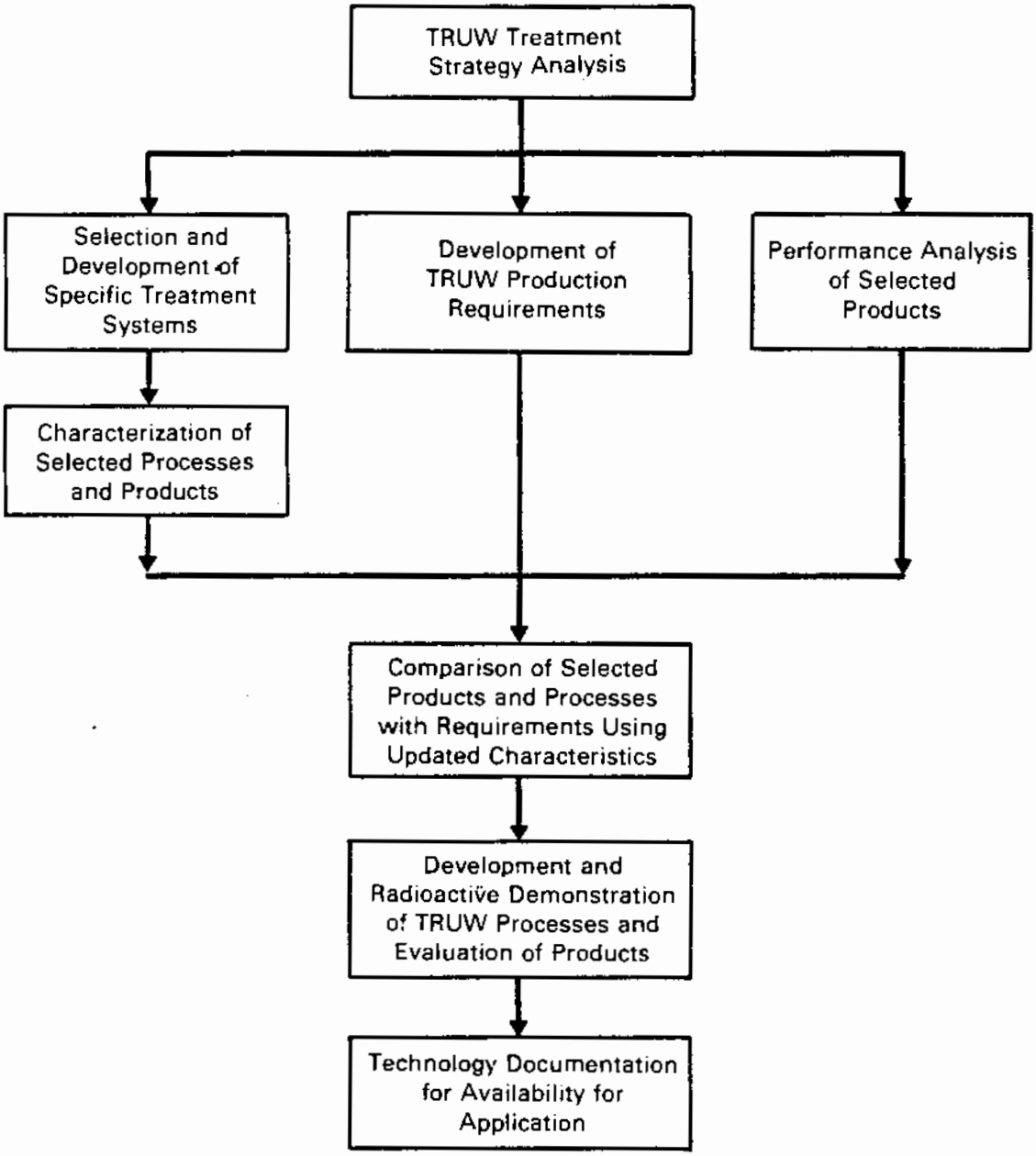

FIGURE 3.1. Major Steps in TRUW Treatment Development Program

(e.g., what type of incinerator?) and their development, if needed; 2) development of TRU waste production requirements (i.e., criteria) with concurrence from the repository program staff to ensure that the products will be compatible with the repository systems (e.g,. the limits on size and weight of the containers); and 3) completion of a performance assessment of the selected products in repository environments. After the processes are selected and actual products made, characterization of the selected processes and products can be accomplished. With actual product data, production requirements, and performance analyses completed, a final determination can be made on the appropriateness of the conclusions reached in this document. With confirmation of the conclusions, major development and demonstration activities can be completed to provide the technology to future users with a fully documented technology.

The approach used in this study is illustrated in Figure 3.2. The first step was to identify the study bases, described in Section 4. Data from the Barnwell Nuclear Fuel Plant (BNFP) were used as the primary source for waste type and waste volume information (Darr 1983). Minor modifications in the primary data were made based on data in the literature and the experience of the authors. Waste volumes and waste descriptions are covered in Section 5. The possible treatment options for each type of waste were then considered, as described in Section 6. Six objectives were established for selecting treatment processes: no treatment (Option 1), minimum treatment (Option 2), treatment by one immobilization process (Option 3), maximum volume reduction (Option 4), maximum use of decontamination (Option 5), and preparation of waste forms without combustibles (Option 6).

These objectives were then used to select treatment options. This selection resulted from numerous meetings of the authors in which the effects of various processing combinations were considered; the results of these discussions are described in Section 6. After the selection of the options to be evaluated, the volume of wastes that would be shipped for disposal to the repository or to a LLW facility was determined for each option. Using these volumes, the costs of transportation and disposal were determined and treatment costs were estimated and are included in Section 8. Considerations other than costs are addressed in Section 9. With these data, general recommendations

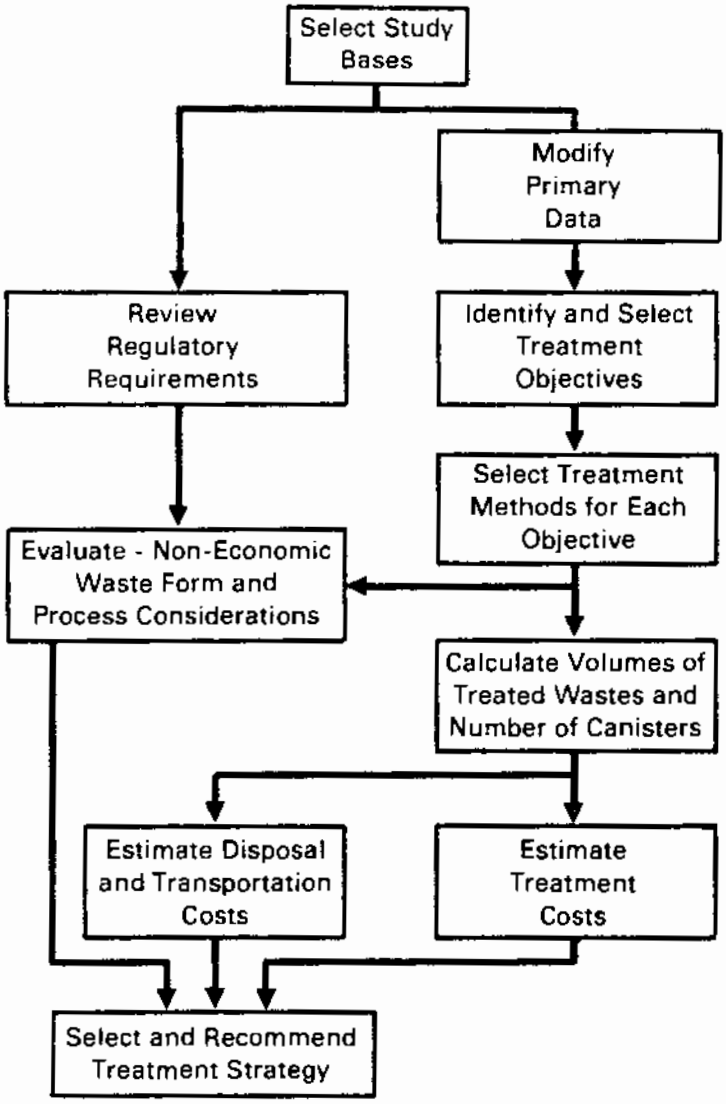

FIGURE 3.2 Flow Chart for Strategy Evaluation

were selected for the treatment strategy discussed in Section 9. Finally, the resulting recommendations for further treatment technology considerations and for the selected treatment options are provided in Section 10.

3.1 REFERENCE

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

4.0 OVERALL BASES FOR STUDY

This section identifies the major technical bases and assumptions used in the study, including regulatory bases. The bases are applied to the overall study approach described in Section 3 and are used for developing the detailed data and analyses in the subsequent sections.

4.1 TECHNICAL BASES AND ASSUMPTIONS

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

- The BNFP is the reference reprocessing plant for this study. The BNFP includes 1) a fuel receiving and storage station, 2) a separations facility, 3) a plutonium dioxide conversion facility, 4) a waste processing facility, 5) waste storage, and 6) a physically separate uranium hexafluoride conversion facility. Although there are no commercial reprocessing plants currently operating in the U.S., the construction of the BNFP was nearly complete when it was discontinued, and the plant is believed to be reasonably representative of the state-of-the-art design of commercial-scale fuel reprocessing plants. In addition, the BNFP staff performed waste management studies specific to that plant for DOE from 1979 to 1983 (Anderson et al. 1979, Anderson and Evans 1983, Boone and Ebel 1983, Darr 1983); these reports provided useful information for this study. This study also used information from a related ongoing study on Waste Management Systems Analyses for DOE's Office of Civilian Radioactive Waste Management (OCRWM).
- All TRUW treatment is assumed to be at the reprocessing plant, not at a central treatment, storage, or repository facility.
- High-level liquid waste (HLLW) and raffinates from downstream solvent extraction cycles are combined in the normal plant flowsheet and are converted to a borosilicate glass as HLW. Thus HLW is excluded from this study, except in the cases where some of the TRUW is combined

with HLW. In these cases, the incremental impacts of the TRUW addition to HLW are identified and evaluated.

- Existing information is used for characterizing the TRUW from the reference reprocessing plant. Most of the information used is taken from the Darr (1983) study and from DOE/ET-0028 (U.S. DOE 1979); these sources are believed to be the most comprehensive analyses related to the needs of this study. Appropriate adjustments have been made here to some of the information from these sources.

- All waste streams in the reference fuel reprocessing plant that could potentially be designated as TRUW are considered in this study. However, all streams that are indicated by Darr (1983) to be non-TRUW are excluded as TRUW here. This assumes that an efficient assay system is in place in the facility to discriminate accurately between waste streams that are TRUW and those that could be, but are not, TRUW. Some sensitivity analyses were conducted to determine whether factors of ±3 in TRU nuclide concentrations in waste streams would change the classification of the wastes.

- The definition of TRUW used here is from the fourth working draft of the proposed regulation 40 CFR 191 (U.S. EPA 1984a): "'Transuranic wastes', as used in this Part, means wastes containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste." Corrections are applied, as described in 10 CFR 60 (U.S. NRC 1984a) and 10 CFR 61 (U.S. NRC 1984b), for the allowable amount of beta-emitting ^{241}Pu (a factor of 35 is applied to allow for alpha decay of its daughters), and for short-lived alpha-emitting ^{242}Cm (a factor of 200 is applied to allow for alpha decay of its long-lived daughters). Additional definitions of TRUW are discussed in Appendix C.

- Transuranic waste is assumed to be disposed of in a deep geologic repository concurrently with HLW. The impacts of various TRUW strategies on waste disposal would thus be incremental to the disposal of other wastes resulting from spent fuel recycling. Some of the disposal requirements for TRUW are identified in the

regulations, if it is emplaced in a deep geologic repository. Since TRUW is excluded from shallow-land burial, the use of deep geologic disposal appears to be a reasonable assumption for this study.

- Detailed waste form requirements at a repository are currently unknown. The treatments studied include a broad range of waste form characteristics.
- Processing concepts within the reference reprocessing plant for the various treatment systems are based primarily on work by former BNFP staff, with modifications made by the authors of this study to ensure consistency.
- Costs of the treatment processes within the reference reprocessing plant are based primarily on those provided by McKee et al. (1984), with modifications made for differences in bases. Research and development and decommissioning needs and their costs are not evaluated. Costs are based on undiscounted 1983 dollars.
- Only one reference transportation system is defined and used for TRUW. The system assumed is that used in the McKee et al. (1984) study. Transportation costs are based on information from the same source as the McKee report.
- The reference repository is located in basalt, using the BWIP design (Kaiser Engineers Inc./Parsons, Brinkerhoff, Quade, and Douglas, Inc. 1983). Disposal costs are determined using the Repository Economics (RECON) model (Clark et al. 1983).
- Costs for LLW disposal are based upon the cost schedule of Chem-Nuclear Systems dated January 1, 1984 (Chem-Nuclear Systems, Inc. 1984).
- Reprocessed fuel is assumed to have received an average integrated exposure of 28,500 megawatt days per metric ton heavy metal (MWD/MTU). Wastes are assumed to be from spent fuel that is 9 years out-of-reactor (Darr 1983).

- No extended interim onsite storage of TRUW is considered in this study, except for lag storage needed before and after processing. The impacts of various onsite lag storage strategies would require a separate evaluation.

4.2 REGULATORY BACKGROUND

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 concerning TRUW management with respect to their potential impact on the selection of TRUW treatment strategies and subsequent waste management steps. Additional details are given in Appendix C.

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 1984a). This regulation applies to the waste management steps of waste generation, treatment and storage, and the filling and presealing of waste disposal repositories. It does not, however, apply to disposal. The basic federal regulation for radioactive waste disposal is stated in draft 40 CFR 191 (U.S. EPA 1984b, 1985); however, the part of this regulation dealing specifically with waste form/repository performance requirements has not been finalized.

The basic NRC regulation, "Standards for Protection Against Radiation," is stated in 10 CFR 20 (U.S. NRC 1983c). This regulation gives some dose limits and references 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 radiation protection of the public 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 171-178 (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 concerns containment, which is generally provided by the outer transportation packaging [i.e., the cask for remotely handled TRUW (RH TRUW), or the Transuranic Package Transporter (TRUPACT) packaging for contact-handled TRUW (CH TRUW)].

4.2.2 Regulations Relating to Release Rates from Repositories (i.e., regulations that may be related to waste forms)

Detailed regulations and requirements for commercial TRUW forms are not currently available. However, regulations have been developed for HLW (10 CFR 60) and LLW (10 CFR 61) by NRC, and have been proposed for waste disposal by EPA (40 CFR 191). 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, 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 defense TRUW to be sent to the Waste Isolation Pilot Plant (WIPP) (Westinghouse 1984).

In anticipating requirements for commercial TRUW, a range of possibilities has been considered. The minimum requirements would likely be those which 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 is to be disposed of in a commercial geologic repository. It is the purpose of this section to identify all of the potential requirements which could be applicable to TRUW forms and canisters. Table 4.1 has been constructed to provide a perspective of the potential disposal requirements for TRUW. It is recognized that some of the requirements (e.g., those that are concerned with subsidence on the LLW site) may not be applicable to deep geologic repository disposal. We have therefore not selected strategies for evaluation based solely on their ability to meet the most stringent requirements. A discussion of the waste form needs as they relate to release rates from repositories is provided in the following subsections.

TABLE 4.1. Summary of the Regulations/Criteria Related to TRUW Form/Canister Requirements[a]

No.	Characteristic	Requirements Source	Composite Bases from 10 CFR 61, 40 CFR 191, WIPP and BWIP WAC
1	Canister	WIPP	Noncombustible; 25+ year life
		10 CFR 61	300 year life with poor waste forms (see "other" below); pass Type A transportation requirements; maintain containment during transportation, emplacement, retrieval
2	Package characteristics	10 CFR 60	Chemical-physical-nuclear characteristics compatible with repository; 300 to 1,000 year 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 year container, resistant to radiation (1E8 Rad γ); resistant to biodegradation test, leaching, breakdown from water immersion, and breakdown from thermal cycling test; compressive strength >50 psi
		10 CFR 60	Not dispersible; particles to be consolidated
		WIPP	<1%/can must be <10 μm particles
5	Waste form combustibility	10 CFR 60	Must be noncombustible unless shown that fire will not compromise safety
		BWIP	No organics allowed
6	Free liquid content	10 CFR 61	<0.5 wt%; need double the minimum amount absorbent
		WIPP	Sludges OK if canister is corrosion protected
7	Explosives content	WIPP	None allowed
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; radionuclides must be <1 wt% of waste
10	Gaseous waste	10 CFR 61	Pressure <1.5 atm at 20°C; <100 kg/m^3 in other containers
11	Gas generation	WIPP	<270 kg/m^3 organic in 55-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 also branch position paper requirements for LLW below
13	Structural stability	10 CFR 61	Form or container must be structurally stable in disposal environment; see also branch position paper for LLW below
14	Void spaces	10 CFR 61	Reduce to extent practical
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; alpha radionuclides to aquifer in 1000 years shall be <15 pCi/L
		10 CFR 60	From engineered barrier, <1E-5/yr of 1000 year inventory; not applicable to radionuclides released <0.1% of calculated total release rate
16	Dose to public	40 CFR 191	<25/75/25 mrem/yr + ALARA; <4 mrem/yr + γ from radionuclide in aquifer
17	Identification	10 CFR 60	Permanent and unique
18	Other	10 CFR 61	Branch technical position paper (U.S. NRC 1983) gives details on waste form requirements: compressive strength >50 psi per ASTM C39 after all tests: - Expose to 1E+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 B553, Section 3 - Destructive analysis to assure homogeneity Or for 300 year container: - Strength with 120 lb/ft^3 overburden - Resistant to 1E+8 Rad - Resistant to biodegradation test as above - Resistant to thermal cycling as above - Positive steel - Contents inspectable - Passive vent - Withstand 3 G lifting load
		WIPP	CH <3.5 W/m^3; RH <300 W/can; <200 g fissile/55-gal drum; dose CH *200 mrem/hr; dose RH <100 rem/hr; <5 g/ft^3 fissile RH

(a) See Table C.1 for more information.

4.2.2.1 EPA Requirement for TRUW

The fifth working draft of 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 wastes acceptable for shallow land burial, provided in 10 CFR 61, and also include some radionuclides not specifically identified in 10 CFR 61. It should be noted, however, that the fourth working draft of 40 CFR 191 deletes the table that gives 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 of amounts of TRUW constituents that can be released per 1 million curies of TRU nuclides present in TRUW to the accessible environment over a period of 10,000 years. From calculations in this study, 1 million curies of TRU nuclides in TRUW result from reprocessing 84,000 MT of the reference spent fuel, and TRUW from reprocessing plants contains about 0.225% of the TRU nuclides present in the original spent fuel. Based on information in DOE/ET-0028, Volume 1, the TRU nuclides in TRUW from MOX fuel refabrication plants are about 0.12% of the TRU nuclides present in spent fuel. By including the amount of TRU nuclides in TRUW from both fuel reprocessing and MOX fuel reprocessing, 1 million curies of TRU nuclides in TRUW will result from 55,000 MT of original spent fuel. Note that the amount of TRU nuclides in spent fuel is about 1/0.00345, or 290 times that in the equivalent amount of TRUW produced from reprocessing of spent fuel. However, the EPA-proposed regulations recognize a factor of only 55. Thus the proposed 40 CFR 191 is a factor of about 290/55, or 5.3 times more conservative for allowable release rates from equivalent amounts of TRU nuclides in TRUW compared with those in spent fuel. (See Item 15 in Table 4.1.) This factor of 55 for the performance requirements of TRUW forms in a repository is lower than the factor for spent fuel and only applies to the waste form portion of the series of barriers that retard releases of waste constituents from a repository.

The same kind of reasoning can be applied to the fission and activation products in TRUW. The total fraction of fission products in TRUW from fuel reprocessing (there are essentially no fission products in TRUW from MOX fuel

refabrication plants) is about 0.71% of the amount in spent fuel (based on Darr 1983). Thus the performance requirement for the waste form plus canister and for other barriers could be reduced by a factor of about 140 for the fission products in TRUW.

Essentially all of the activation products in irradiated fuel eventually are in the TRUW (fuel cladding and hardware); these activation products comprise about 1.5 times the number of curies of fission products present in TRUW. Carbon-14 is the only activation product that appears in EPA's list of specific isotopes of concern; thus all other activation products can be put into EPA's category of all other non-TRU nuclides. The EPA's limit for releases of these other non-TRU nuclides is the same as for the fission products ^{135}Cs, ^{137}Cs, ^{90}Sr, and ^{126}Sn. Thus the performance requirement for the waste form plus canister for the activation products could be reasoned to be higher by a factor of about 1.5 than those for fission products in TRUW. Application of this factor of 1.5 to the inverted factor of 140 derived in the previous paragraph implies that the performance requirement for the waste form plus canister for the activation products in TRUW is a factor of about 140/1.5, or 93 times lower than that for fission products in spent fuel. For ^{14}C, there are about 0.74 and 0.11 Ci/MT of spent fuel in the fuel itself and in the fuel cladding hulls (TRUW), respectively, for a total of about 850 Ci/1,000 MT of spent fuel. The allowable release rate of 100 Ci/1,000 MT in the proposed 40 CFR 191 would allow about 12% of the ^{14}C to be released to the accessible environment from the waste form and canister and from the repository and geologic barriers.

4.2.2.2 NRC Requirements for TRUW

The NRC has not developed regulations specific to TRUW form or disposal requirements, but their regulations relating to HLW in 10 CFR 60 are stated to be applicable to all radioactive wastes that are disposed of in a geologic repository. It is further emphasized in the discussion of the bases for the NRC regulations that release requirements for radionuclides in TRUW that are disposed of in a geologic repository are the same as those for high-level waste.

Regulation 10 CFR 60 states that containment within the waste packages will be substantially complete for a period of at least 300 but no more than

1,000 years after closure of a repository. In addition, the release rate from the engineered barrier system (which includes any canister overpack, backfill materials, and the entire underground facility) shall not exceed 1 part in 100,000 per year 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.)

4.2.2.3 Requirements Regarding Release Rates from Waste Forms

Fractional release rate requirements directly from the waste forms cannot be obtained directly from the existing NRC or the proposed EPA regulations. This is 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. However, by extrapolating from currently proposed EPA regulations, it can be concluded that, for the equivalent amount of spent fuel, allowable fractional release rates to the accessible environment from TRUW are as follows: for TRU nuclides, about 50 times higher than those from spent fuel; for fission products, about 140 times higher than those from spent fuel; and for activation products, about 90 times higher than those from spent fuel. The NRC release rate limit from the engineered barrier system of 1 part in 100,000/yr may be taken to be applicable to TRU nuclides in TRUW in a deep geologic repository.

4.2.2.4 Repository Waste Acceptance Requirements

High-level waste acceptance requirements for the Basalt Waste Isolation Project (BWIP) have been drafted and provide some additional indications on requirements for the waste going to the repository. Specifically, BWIP, in its concern for the potential of organic complexes forming in the repository and enhancing the migration of actinides, 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 another repository with this requirement, it may well be expected that the TRUW would have to meet this requirement as well.

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 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 WIPP Waste Acceptance Criteria (WAC) for defense TRUW (Westinghouse Electric Company 1984), and the draft HLW acceptance requirements for BWIP (Randlev 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.

Section 9 provides additional discussion of the requirements shown in Table 4.1 as they relate to the specific waste forms considered in this study. Additional related material is presented in Appendix C.

4.3 REFERENCES

Anderson, K. J., et al. 1979. Engineering Evaluation of Waste Handling and Storage Facilities. AGNS-35900-4.2-26, Allied-General Nuclear Services, Barnwell, South Carolina.

Anderson, K. J. and T. A. Evans. 1983. An Evaluation of General Process Trash Disposal by Compaction. ONI/3142/RD-03, Allied-General Nuclear Services, Barnwell, South Carolina.

Boone, F. W., and P. E. Ebel. 1983. Feasibility Evaluation of Disposing of Spent Fuel and Fittings at a Shallow-Land Burial Site. ONI/3141/RD-01, Allied-General Nuclear Services, Barnwell, South Carolina.

Chem-Nuclear Systems, Inc. 1984. Barnwell Low-Level Radioactive Waste Disposal Facility Rate Schedule. Chem-Nuclear Systems, Inc., Barnwell, South Carolina.

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

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

Kaiser Engineers Inc./Parsons, Brinkerhoff, Quade, and Douglas, Inc. 1983. Conceptual System Design Description, Nuclear Waste Repositories in Basalt, Project B-301. BWI-SD-006, Rockwell Hanford Operations, Richland, Washington.

McKee, R. W., L. L. Clark, P. M. Daling, J. F. Nesbitt, and J. L. Swanson. 1984. "Economic Analysis of Waste Management System Alternatives for Reprocessing Wastes." Waste Management 1984, pp. 383-393. University of Arizona, Tucson.

Randklev, E. H. 1983. Draft Waste Acceptance Requirements for the Basalt Waste Isolation Project. SD-BWI-CR-018, Rockwell Hanford Operations, Richland, Washington.

U.S. Department of Energy. 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028 in 5 volumes, U.S. DOE, Washington, D.C.

U.S. Department of Transportation. 1984. Code of Federal Regulations, Title 49, Transportation (subchapter C - Hazardous Material Regulations); Part 171, General Information, Regulations and Definitions; Part 172, Hazardous Materials Table and Hazardous Materials Communications Regulations; Part 173, Shippers General Requirements for Shipments and Packagings; Part 174, Carriage by Rail; Part 177, Carriage by Public Highway; Part 178, Shipping Container Specifications. Revised January 1, 1982. U.S. DOT, Washington, D.C.

U.S. Environmental Protection Agency. 1984a. Code of Federal Regulations, Title 40, Protection of Environment; Part 190, Environmental Protection Standards for Nuclear Power Operations. Revised January 1, 1984. U.S. EPA, Washington, D.C.

U.S. Environmental Protection Agency. 1984b. Fourth Working Draft. Code of Federal Regulations, Title 40, Protection of Environment; Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level, and Transuranic Radioactive Wastes. April 17, 1984. U.S. EPA, U.S. Public Document Room, Washington, D.C.

U.S. Environmental Protection Agency. 1985. Fifth Working Draft. Code of Federal Regulations, Title 40, Protection of Environment; Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes. March 21, 1985. U.S. EPA, U.S. Public Document Room, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1983. Low-Level Licensing Branch Technical Portion on Radioactive Waste Classification. May 1983, Revision D. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984a. Code of Federal Regulations, Title 10, Energy; Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories (Subpart E, Technical Criteria). Final Rule, U.S. Federal Register, Vol. 48, No. 120, June 21, 1983, pp. 28194-28229. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984b. Code of Federal Regulations, Title 10, Energy; Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, Final Rule. U.S. Federal Register, Vol. 47, December 27, 1982 (Effective January 26, 1983), p. 57463. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984c. Code of Federal Regulations, Title 10; Energy; Part 20, Standards for Protection Against Radiation. Revised January 1, 1983. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984d. Code of Federal Regulations, Title 10, Energy; Part 71, Packaging and Transportation of Radioactive Material. U.S. Federal Register, Vol. 48, p. 35607, August 5, 1983; p. 38449, August 24, 1983. U.S. NRC, Washington, D.C.

Westinghouse Electric Company. 1984. TRU Waste Acceptance Criteria for the Waste Isolation Pilot Plant. WIPP-DOE-069, Rev. 2, Draft C, Albuquerque, New Mexico.

5.0 DEFINITION OF TRUW STREAMS

The TRUW quantities and radionuclide contents used in this report are primarily as estimated by Allied-General Nuclear Services (AGNS) personnel for operation of the BNFP (Darr 1983). Those estimates that were modified by the authors of this report are discussed later in this section. The wastes and the containers that the BNFP staff planned to use are briefly described and the quantities are summarized in a series of tables. Only the waste streams in Darr (1983) that are indicated to be TRUW are taken as such. This assumes that an efficient assay system is in place in the existing facility to discriminate accurately between streams that are TRUW and those that could be, but are not, TRUW.

5.1 ORIGIN OF GENERAL TRUW TYPES AT THE REFERENCE FUEL REPROCESSING PLANT

The hulls and hardware are the metallic (Zircaloy, Inconel, and stainless steel) portions of the spent fuel elements; these portions remain after the elements are sheared and the uranium dioxide fuel is dissolved out with nitric acid during reprocessing. The hulls and hardware are not only the most voluminous and heaviest TRUW type, they are also the most highly radioactive.

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

Used HEPA filters comprise a large volume waste stream that presents some challenging treatment problems. The filters have either wooden or metallic frames and noncombustible (e.g., glass, asbestos) or combustible (e.g., filter paper) filter media. They also contain an appreciable amount of organic materials in the form of adhesives and rubber gaskets. Some filters also contain separators made of aluminum.

Failed equipment comprises another metallic (primarily stainless steel) waste stream. Darr's (1983) estimates indicate that this is a low volume waste stream. The BNFP staff planned to store large pieces of failed equipment

onsite until the plant was decommissioned, at which time the failed equipment would be treated along with (and considered as) decommissioning waste.

Fluorinator solids are a residue of fluorination of the uranium product of the reprocessing plant. This waste stream is composed primarily of alumina and calcium fluoride particulates.

5.2 BASES FOR TRUW DESCRIPTIONS

The Darr study (1983) described 18 different waste streams that are classified as TRUW. Many of these were further categorized according to container size, TRU content, and surface dose rate. The study also described other streams of similar wastes that did not contain enough TRU activity to be classed as TRUW; these streams are not addressed here.

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

The following bases for the GPT and SAC wastes were adopted based on some of the values from the Darr study, combined with the authors' knowledge of waste compositions and handling practices:

- The GPT wastes are segregated at the point of origin, so that the fraction of the combustible waste is equal to the fraction of the GPT containers that contain combustible wastes. All of the GPT wastes are 80 vol% combustible and 20 vol% noncombustible materials. Only for the GPT from the Plutonium Product Facility do these bases give quantities different from those given in the Darr study.

- The SAC wastes are not segregated at the point of origin, so all of the containers contain both combustible and noncombustible wastes, as indicated in Appendix C of the Darr study. Each SAC waste container holds a mixture of 60 vol% combustible and 40 vol% noncombustible waste; these somewhat arbitrary fractions are based on the authors' interpretation of information for SAC waste stream 23 in Appendix B of the Darr study. These bases give different quantities than those in Darr's Appendix C for both of the SAC waste streams.

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

Another important consideration not evident in the BNFP staff estimates is that all HEPA filters, even those with metal frames, contain an appreciable amount of organic material. All of this waste stream must therefore be considered partially combustible, even though Darr applied that designation only to the wood-framed filters.

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

5.3 TRUW QUANTITIES

The tables presented in this section summarize the number of containers for the wastes and the volumes, weights, and radiation levels of the TRUW. These summaries were derived from the detailed values given in Appendix A, which were modified as indicated above from the Darr study.

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

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

Table 5.1 contains a summary of the Darr estimates of the numbers of initial waste containers produced each year to reprocess spent fuel at a rate of 1,500 MTU/yr. The initial containers are those in which the wastes are collected and moved from the part of the facility where they were generated. The results are tabulated by container size and type of waste and are allocated among several dose rate ranges. These values are based on the data contained in Darr (Appendix C), without including the container weight in defining the TRU level. (Note that if the weight of the container had been included, there would have been some decrease in the quantity of TRUW and a corresponding increase in the quantity of Class C LLW. The overall effect of this change, however, would be small.)

The wastes from the iodine retention operations are excluded from Table 5.1 and from subsequent consideration, since technically they are not TRUW because of the special disposal requirements for such wastes and because of their small volume. The use of appropriate operating practices, including waste assay techniques, is assumed in this study to support this basis.

Table 5.2 contains a summary of the volumes occupied by the initial containers, again using values provided by Darr. In this and subsequent tables the quantities are given per MTU processed. The volumes in this table represent the volumes of waste to be disposed of if disposal in the initial containers is possible.

The volumes of untreated wastes before they are placed in the initial containers are given in Table 5.3. These values represent the starting volumes

TABLE 5.1. Containers per Year of Untreated TRUW[a]

Container Size and Waste Type	Stream Number[a]	Containers/yr in Dose Rate (mR/hr) Range				Totals		
		<200	200-10^3	10^3-10^4	>10^4	CH TRUW	RH TRUW	Total
55-gal drums								
General process trash (GPT)								
Segregated combustible	27,53,65	432	84	74.4	--	432	158.4	590.4
Segregated noncombustible	27,53,65	108	21	18.6	--	108	39.6	147.6
Total GPT						540	198	738
Failed equipment	51A	70	--	--	--	70	--	70
Fluorinator solids	41	--	93	--	--	--	93	93
Metal-framed filters	52B	50	--	--		50	--	50
Total in 55-gal drums						660	291	951
80-gal drums								
Wood-framed filters	25B	153	52	12	--	153	64	217
Metal-framed filters	25B,45,52A,63B	961	56	13	--	961	69	1,030
Total in 80-gal drums						1,114	133	1,247
600-gal containers								
Hulls and hardware	21	--	--	--	300	--	300	300
Failed equipment	24,51B,62	4	1	2	1	4	4	8
Metal-framed filters	25C,63A	--	--	--	44	--	44	44
Sample and analytical cell (SAC) waste	23,67	--	28	6	3	--	37	37
Total in 600-gal containers						4	385	389
Total all containers						1,778	809	2,587

(a) Data and stream numbers are taken from Darr (1983) for reprocessing 1,500 MTU/yr. Container weights not included in defining TRUW level. Wastes from iodine retention operations not included (78 55-gal drums/yr). Values may be converted to drums/MTU by dividing by 1,500.

TABLE 5.2. Annual Volumes of Containers of Untreated TRUW[a]

Container Size and Waste Type	Stream Number[a]	Volume of TRUW in Indicated Dose Rate (mR/hr) Range, m^3/MTU				Totals		
		200	200-10^3	10^3-10^4	>10^4	CH TRUW	RH TRUW	Total
55-gal drums								
General process trash (GPT)								
Segregated combustible	27,53,65	0.074	0.014	0.013	--	0.074	0.027	0.101
Segregated noncombustible	27,53,65	0.019	0.0036	0.0032	--	0.019	0.0068	0.026
Total GPT						0.093	0.034	0.127
Failed equipment	51A	0.012	--	--	--	0.012	--	0.012
Fluorinator solids	41	--	0.016	--	--	--	0.016	0.016
Metal-framed filters	52B	0.0086	--	--	--	0.0086	--	0.0086
Total in 55-gal drums						0.114	0.050	0.164
80-gal drums								
Wood-framed filters	25B	0.036	0.012	0.0028	--	0.036	0.015	0.051
Metal-framed filters	25B,45,52A,63B	0.225	0.013	0.0030	--	0.225	0.016	0.241
Total in 80-gal drums						0.261	0.031	0.292
600-gal containers								
Hulls and hardware	21	--	--	--	0.482	--	0.482	0.482
Failed equipment	24,51B,62	0.0064	0.0016	0.0032	0.0016	0.0064	0.0064	0.013
Metal-framed filters	25C,63A	--	--	--	0.071	--	0.071	0.071
Sample and analytical cell (SAC) waste	23,67	--	0.045	0.010	0.0048	--	0.059	0.059
Total in 600-gal drums						0.0064	0.618	0.625
Total all containers						0.381	0.699	1.081

(a) Data and stream numbers are taken from Darr (1983).
Volume values were obtained from:
- Containers/yr from Table 5.1.
- 1,500 MTU/yr reprocessing rate.
- Volumes occupied by containers as in Darr (1983:28).
- 55-gal drum occupies 0.258 m^3 (9.1 ft^3).
- 80-gal drum occupies 0.351 m^3 (12.4 ft^3).
- 600-gal container occupies 2.41 m^3 (85 ft^3).

TABLE 5.3. Unit Volumes of Untreated TRUW Before Containerization[a]

Container Size and Waste Type	Stream Number[a]	Volume of TRUW in Indicated Dose Rate (mR/hr) Range, m^3/MTU				Totals		
		200	$200-10^3$	10^3-10^4	$>10^4$	CH TRUW	RH TRUW	Total
55-gal drums								
General process trash (GPT)								
Segregated combustible	27,53,65	0.056	0.0113	0.0100	--	0.056	0.0214	0.0774
Segregated noncombustible	27,53,65	0.0140	0.00283	0.00251	--	0.0140	0.00534	0.0193
Total GPT						0.070	0.0267	0.0967
Failed equipment	51A	0.00944	--	--	--	0.00944	--	0.0094
Particulate solids	41	--	0.0117	--	--	--	0.0117	0.0117
Metal-framed filters	52B	0.00283	--	--	--	0.00283	--	0.0028
Total in 55-gal drums						0.0823	0.0384	0.121
80-gal drums								
Wood-framed filters	25B	0.0102	0.00347	0.00054	--	0.0102	0.00401	0.0142
Metal-framed filters	25B,45,52A,63B	0.0655	0.00363	0.00087	--	0.0655	0.00449	0.0700
Total in 80-gal drums						0.0757	0.0085	0.0842
600-gal containers								
Hulls and hardware	21	--	--	--	0.425	--	0.425	0.425
Failed equipment	24,51B,62	0.00378	0.00094	0.00227	0.00094	0.00378	0.0042	0.0080
Metal-framed filters	25C,63A	--	--	--	0.0113	--	0.0113	0.0113
Sample and analytical cell (SAC) waste	23,67	--	0.0107	0.00629	0.00215	--	0.0191	0.0191
Total in 600-gal containers						0.00378	0.460	0.463
Total all wastes						0.1618	0.507	0.668

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

for waste treatment processes and are occasionally much smaller than the volumes of the initial containers because of inefficient packing; this is especially important with filters that are packaged individually in drums. These volumes of untreated wastes were obtained by calculating the volumes of untreated wastes per container from the data in Appendix B of the Darr study and by multiplying those values by the number of containers filled per MTU processed.

Table 5.4 contains the weight of the various wastes. These data also come directly from the Darr study.

Table 5.5 presents a summary comparison of the volumes of the initial waste containers containing the different types of wastes. Because of their initially high volumes and low packing density, the potential volume reductions are the greatest for the hulls and hardware, the filters, and the GPT.

The potential impact of a plus-or-minus threefold uncertainty in the Darr radionuclide content estimates on the TRUW quantities is addressed in Table 5.6. This uncertainty range, chosen arbitrarily, has relatively little effect on the volume of the various classes of most of the waste types. However, the fluorinator solids provide a case in which a large degree of variability could occur; the quantity of TRUW of this type could vary from zero to 4 times the quantity that is based on the AGNS estimate. This large a variability should be kept in mind when designing and evaluating alternative treatment processes for this waste.

5.4 REFERENCE

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

TABLE 5.4. Unit Weights of Untreated TRUW Before Containerization[a]

Container Size and Waste Type	Stream Number[a]	Weight of TRUW in Indicated Dose Rate (mR/hr) Range, kg/MTU				Totals		
		<200	200-10^3	10^3-10^4	>10^4	CH TRUW	RH TRUW	Total
55-gal drums								
General process trash (GPT)								
Segregated combustible	27,53,65	6.05	1.18	1.04	--	6.05	2.22	8.27
Segregated noncombustible	27,53,65	1.51	0.29	0.26	--	1.51	0.55	2.06
Total GPT						7.56	2.77	10.33
Failed equipment	51A	9.33	--	--	--	9.33	--	9.33
Particulate solids	41	--	20.65	--	--	--	20.65	20.65
Metal-framed filters	52B	1.27	--	--	--	1.27	--	1.27
Total in 55-gal drums						18.16	23.42	41.58
80-gal containers								
Wood-framed filters	25B	1.326	0.451	0.104	--	1.326	0.555	1.88
Metal-framed filters	25B,45,52A,63B	8.329	0.485	0.113	--	8.329	0.598	8.93
Total in 80-gal drums						9.655	1.153	10.81
600-gal drums containing:								
Hulls and hardware	21	--	--	--	324.0	--	324.0	324.0
Failed equipment	24,51B,62	2.40	0.60	1.20	0.60	2.40	2.40	4.80
Metal-framed filters	25C,63A	--	--	--	1.32	--	1.32	1.32
Sample and analytical cell (SAC) waste	23,67	--	1.475	0.316	0.158	--	1.949	1.95
Total in 600-gal containers						2.40	329.7	332.07
Total all wastes						30.2	354.2	384.4

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

TABLE 5.5. Comparison of Untreated TRUW Quantities

Waste	Volume of Initial Waste Packages, m^3/MTHM			Volume of Waste Before Packaging, m^3/MTHM	Initial Packaging Factor	Density of Waste Before Packaging, kg/m^3
	CH TRUW	RH TRUW	Total TRUW			
Hulls and hardware	--	0.482	0.482	0.425	0.9	760
Filters	0.270	0.102	0.372	0.098	0.3	130
GPT	0.093	0.034	0.127	0.097	0.8	100
SAC waste	--	0.0598	0.0598	0.019	0.3	100
Failed equipment	0.0184	0.0064	0.0232	0.0174	0.8	600-700
Fluorinator solids	--	0.016	0.016	0.0117	0.7	1800
Total	0.381	0.700	1.08	0.668		

TABLE 5.6. Maximum Possible Variation in Initial Waste Quantities Resulting from Plus or Minus Three-Fold Uncertainties in TRU Radionuclide Concentrations[a]

Waste	Volume of Initial Waste Packages Relative to Reference Case[b]		
	CH TRUW	RH TRUW	Total TRUW
Hulls and hardware	--	1.0	1.0
Filters	0.8 to 1.0	0.7 to 1.6	0.9 to 1.0
GPT	0.7 to 0.8	0.5 to 2.4	0.7 to 1.2
SAC waste	∞[c]	0.4 to 1.0	1.0 to 1.1
Failed equipment	1.0	1.0 to 2.0	1.0 to 1.2
Fluorinator solids	--	0.0 to 4.0	0.0 to 4.0

(a) Assuming that all containers for which classification could be changed in a given direction by a three-fold change in radionuclide concentration were changed in that direction.
(b) Values for the reference case are given in Table 5.5.
(c) There is no CH TRUW in the reference case.

6.0 SELECTION OF WASTE TREATMENT OPTIONS

Both the types of wastes and the types of treatment processes need to be considered in the selection of waste treatment options. The types of wastes were described in Section 5. In this section the types of treatment and a selection of treatment methods for each waste type are presented for the six options identified in Section 3.

6.1 TREATMENT PROCESSES

The treatment processes that could be applied to each of the wastes were considered. The results are summarized in Table 6.1 and discussed briefly below. They are grouped by pretreatment, intermediate treatment, and immobilization. The no treatment option is also included. As shown, the treatment processes can be used for more than one type of waste, and several processes are available for each waste type. For pretreatment,

- all wastes will be assayed at least once (and possibly several times) as they are processed to allow sorting between TRUW and LLW and between CH and RH
- segregation of the wastes will be required for some processing techniques such as incineration--segregation could be performed at the waste generation point or at a central point
- size reduction or shredding of the wastes will be necessary for several of the processes.

Several intermediate methods for preparing the wastes for immobilization or further treatment were considered:

- Decontamination can be used to concentrate contamination in a smaller mass of decontamination residues and thus allow a change in classification of the majority of the waste from TRUW to LLW.
- Metallic wastes can be oxidized and then treated as a ceramic for incorporation into cement, glass, or other forms. Oxidation could also be used to reduce the volume of odd shapes and sizes to allow higher bulk densities.

TABLE 6.1. Applicability of Treatment Method To Waste Types

Treatment Methods	Major Waste Types: Metallic Wastes	Plastics and Other Combustibles	Ash, Sludge, Powdered Solids	Filters	Liquid Wastes
No treatment	X	X	X	X	
Pretreatment					
Assay	X	X	X	X	X
Segregation	X	X		X	
Size reduction	X	X		X	
Intermediate processes					
Decontamination	X	X		X	X
Oxidation	X				
Incineration		X		X	
Slagging pyrolysis	X	X	X	X	
Precipitation					X
Ion exchange					X
Calcination/ evaporation					X
Dissolution	X	X	X	X	
Acid digestion		X		X	
Combination with HLW			X		X
Dilution to LLW	X	X	X	X	X
Immobilization					
Melting	X		X	X	
Encapsulation	X	X	X	X	
Compaction	X	X		X	
Cement immobilization	X	X	X	X	X
Vitrification			X		X
Hot pressing	X	X	X		

- Incineration of combustibles can reduce waste volumes and increase the stability of the wastes for disposal.
- Liquid wastes can be decontaminated by several different techniques, such as precipitation and ion exchange, and then treated as LLW.
- Liquid wastes can also be dried by calcination or other techniques to reduce their volume.
- Dissolution or acid digestion of wastes can be used to form a solution containing the waste materials, which will facilitate their processing by techniques such as vitrification.

- A small volume waste stream can be incorporated into another waste stream (such as HLW) if the two streams are chemically compatible.
- If the wastes are slightly over the 100 nCi/g limit for low-level classification, they may become LLW if they are immobilized for disposal by cementation or some other technique that increases their mass. Intentional dilution for reducing the classification of wastes is not expected to be politically acceptable on a large scale, but it may be appropriate for some streams, i.e., those in which conversion to a better final form is indicated, and in which the conversion process itself provides dilution.

The final immobilization processes prepare the wastes for transportation, interim storage, and disposal. Some of these processes are listed below.

- Melting provides the highest volume reduction. Most materials can be melted, although processing at very high temperatures can be difficult and/or complex, and the volatility of some radionuclides may cause secondary processing difficulties.
- Wastes can be encapsulated in a variety of materials with or without size reduction.
- Compaction of the wastes is a simple technique to provide volume reduction, but it does not improve the durability of the wastes.
- Waste may be immobilized in cement, either by encapsulation or by incorporation of waste ions into the cement microstructure.
- Slagging pyrolysis has been considered for TRUW, since it can potentially treat all waste types in one unit. However, it was not given serious consideration in this study because of previous unresolved problems (Tait 1983).
- The potential use of hot pressing for metals, oxides, or selected plastic and rubber has also been recognized but has not been tested for many of these wastes. A process unit could have very different characteristics, depending on the wastes to be treated.

6.2 SELECTION OF TREATMENT OBJECTIVES

As shown in Table 6.1, most treatment methods are only applicable for specific waste types. Even if applicable, treatment may not be optimal for certain waste types. A goal of this study was to include as many of the treatment options as possible for preliminary evaluation. To allow this and to provide a focus for the study, several potential overall strategy objectives were identified, and these are summarized below.

6.2.1 Option 1 - No Treatment

In this option the waste generator (reprocessor) generally prefers to minimize treatment costs, even if doing so increases transportation and disposal costs. Wastes are disposed of as they are generated, without considering their chemical durability, combustibility, or final packaged volumes. The wastes are packaged in containers of the size appropriate to the waste size and to allow efficient handling. Containers of 55-, 80-, and 600-gal capacity were expected to be used at BNFP.

6.2.2 Option 2 - Minimum Treatment (compaction)

For this treatment option the major objective is simple volume reduction. This is to be accomplished with compaction (using pressures of about 1000 psig) in several different systems to save disposal and transportation costs. Supercompaction (using pressures of about 10,000 psig to obtain greater volume reduction) is a similar process but is considered a variation of the primary method. Supercompaction may warrant further evaluation for those cases in which compaction appears to be an attractive treatment method. Some types of wastes, e.g., failed equipment, are not amenable to normal compaction processes. However, it is believed that compaction could be applied to all solid waste types with some success.

6.2.3 Option 3 - Minimum Number of Processes and Products (cementing)

The objectives of this option are to reduce the volume of the wastes, to treat them to limit combustibility and increase chemical durability, and to accomplish both with one major treatment process. The benefits of having only one treatment process include minimizing the capital and operating costs of treatment facilities, and simplifying the characterization and qualification of

the wastes for repository disposal. Cementing was chosen as the sole process in this option because it is a simple and well-developed process that is applicable to all waste types and because it improves the disposal characteristics of the wastes as well. A major disadvantage of the process is its lack of significant volume reduction. Slagging pyrolysis is another potential option, but it is much more complex than cementing; it could be considered for cases in which further improvements to the cement waste form characteristics are needed. Recent experience with slagging pyrolysis at the Idaho National Engineering Laboratory (INEL) has not been very encouraging (Tait 1983). Cementing of the wastes would require that some wastes be pretreated by size reduction or shredding to allow them to be mixed with the cement.

6.2.4 Option 4 - Maximum Volume Reduction Without Decontamination (melting)

One of the major cost factors in waste disposal is the repository disposal cost. Since the repository disposal cost is a function of the volume of the wastes, minimizing the volume of TRUW should be a worthwhile objective. Thus volume reduction is the primary objective of this option; however, it is recognized that this type of processing would also significantly increase the chemical durability of the waste form, particularly if some effort were made to control and adjust compositions. To obtain the minimum volumes in this study, the combustible wastes were assumed first to be incinerated to reduce their volume and mass. Then the residual (ash and scrubber solids) and other wastes were assumed to be processed to maximum theoretical density by incorporation into metal or ceramic melts. Extensive sorting of some wastes would be necessary to facilitate processing.

6.2.5 Option 5 - Maximum Volume Reduction with Decontamination

The primary objective of this option is to reduce the amount of material classified as TRUW. As with Option 4, the major incentive in reducing the TRUW volume is to achieve volume and cost reductions for transportation and disposal. Volume reduction is accomplished by removing surface contamination so that the wastes can be reclassified as LLW after careful assay. It is recognized, however, that disposal of "hotter" LLW may not be less costly than disposal of comparable levels of TRUW. The removed contamination must be disposed

of and should be of low volume. It was therefore determined that the concentrated contamination should be combined with the HLW for vitrification. Such action will reduce the waste treatment units required in the facility (potentially reducing treatment capital and operating costs) while incorporating the wastes into a more durable form. While most wastes could be treated by decontamination, certain fractions of the waste that could not be decontaminated on a practical basis would need to be treated by other processes. Hot pressing of the decontamination sludge from hulls is also considered an alternative to HLW vitrification.

6.2.6 Option 6 - Noncombustible Waste Forms

The objective of Option 6 is to process all wastes into forms that are expected to be acceptable for disposal. A wide variety of disposal criteria have been considered for TRUW; some of the more restrictive criteria would eliminate combustibles from the repository and would require good chemical durability (see Section 4). For this option, all metals would be melted, all combustibles eliminated by incineration, and all residual noncombustible wastes cemented with the incinerator ash and incinerator off-gas scrubber solids to make them resistant to chemical attack and dispersion.

6.3 REFERENCE

Tait, T. D. 1983. Demonstration Test Assessment of the Slagging Pyrolysis Incinerator for Processing INEL Transuranic Waste. EG&G-TF-6192, Idaho National Engineering Laboratory, Idaho Falls, Idaho.

7.0 PROCESS DESCRIPTIONS AND WASTE QUANTITIES FOR THE SIX BASIC TRUW TREATMENT OPTIONS

Each of the six treatment options identified in Section 6 is evaluated here, primarily in terms of its effectiveness in processing TRUW and its processing and disposal costs. Costs are discussed in Section 8, and other processing considerations are discussed in Section 9. The effectiveness of the treatment options depends upon the waste volume reduction achieved and on the final quality of the processed waste form. Table 7.1 summarizes each treatment option for the five TRUW types (described in Section 5): hulls and hardware (H&H), failed equipment, filters, fluorinator solids, and GPT-SAC waste. For the treated and untreated waste forms, CH waste is defined as waste with a surface dose rate less than 200 mR/hr; waste types with surface dose rates greater than 200 mR/hr are categorized as RH waste. Specific surface dose rate calculations were not performed in this study; they were approximated from other analyses.

Each of the treatment options is discussed in the following section, and process and equipment flow diagrams and a summary of the final waste quantities and types are presented. The estimates of the final processed TRUW quantities are given in Appendix B.

Figure 7.1 depicts the overall TRUW processing operations. The block labeled "TRUW Treatment" represents the six TRUW treatment options discussed in subsequent subsections. A new container size (160 gal) was introduced to improve the handling needs for some treated wastes. Characteristics of the various containers are given in Appendix B.

7.1 OPTION 1 - NO TREATMENT

This option involves simply packaging the TRUW as it is generated, holding it in surge storage for a short time, and then shipping it from the reprocessing plant to the waste disposal site. Figure 7.2 shows the steps involved in this option in addition to those given in Figure 7.1. Table 7.2 gives the unpackaged net weights, the unpackaged and packaged waste volumes, and the

TABLE 7.1. Description of Each Treatment Option by Waste Type

Option/Waste Type	Hardware and Hulls	Failed Equipment	Filters	Fluorinator Solids	General Process Trash and SAC Waste	Remarks
1 No treatment	Package as generated	Package as generated	Package as generated	Package as generated	Package as generated	
Container size, gal	TRUW: 600	TRUW: 55, 600	TRUW: 55, 83, 600	TRUW: 55	TRUW: 55, 600	
2 Minimum treatment	RH compact in CH or RH batches	Size reduce as required and RH compact in CH or RH batches	Size reduce as required and RH compact in CH or RH batches	Package as generated	Size reduce as required and RH compact in CH or RH batches	One compactor will compact batches of CH or RH waste
Container size, gal	TRUW: 160	TRUW: 160	TRUW: 160	TRUW: 55	TRUW: 160	
3 Minimum number of processes and products	Premix with cement and package in original container	Size reduce as required. Pour cement over failed equipment in original container.	Shred in either CH or RH shredder. Cement in CH or RH batches in RH in-drum mixer.	Use to replace aggregate for cementing of shredded filters and GPT-SAC waste.	Shred in either CH or RH shredder. Cement in CH or RH batches in RH in-drum mixer.	Aluminum in the filters is a potential problem. May want all RH waste in 600 gal cans. Cementing could transform TRUW to LLW.
Container size, gal	TRUW: 600	TRUW: 55, 600	TRUW: 55	Included in filter and GPT-SAC waste total.	TRUW: 55	
4 Maximum volume reduction without decontamination	Size reduce as required and melt in RH batches in melter	Size reduce as required and then melt in either CH or RH batches in melter	Shred filters in CH or RH shredder. Incinerate shredded filters. Collect metals and melt in CH or RH batches. Melt ash and media in CH or RH batches.	Melt in RH batches in melter	Sort. Melt metals in CH or RH metal batches in melter. RH hot press plastic and rubber in CH or RH batches. Burn cellulose. Melt ash and scrubbing solution residues in either CH or RH batches.	
Container size, gal	TRUW: 160	TRUW: 160	TRUW: 160	TRUW: 240	TRUW: 160	
5 Maximum volume reduction with decontamination	Cryogenic cracking of hulls. Centrifugal decontamination hulls to LLW. Option A: Decontamination solution is vitrified with HLW glass Option B: Decontamination solution is dried and then hot pressed Decontaminate hardware to LLW by vibratory finishing	Sort. Size reduce as required. Compact noncontaminables. Vibratory finish decontaminable failed equipment to LLW. Decontamination solution is vitrified with HLW glass.	Shred in either CH or RH shredder. Incinerate in RH incinerator. Separate metals from ash and media. Vibratory finish metals to LLW. Vitrify ash, residues, media and decontamination solids with HLW glass.	Blend with other fluorinator solids as LLW in RH blender	Sort and size reduce as necessary. Decontaminate portion of the metals and all of the plastic and rubber to LLW. Shred and burn cellulose. Decontaminate scrubbing solution to LLW and cement decontamination solution to TRUW. Vitrify ash, scrubber and decontamination solids with HLW glass. Compact noncontaminable metals with failed equipment.	Chlorine and organics in HLW are potential process problem. Possible pre-oxidation step needed for Zr fines.
Container size, gal	LLW: 160 HLW Suboption A: 85 HLW Suboption B: 53	TRUW: 160 LLW: 160 HLW Suboption A: 85 HLW Suboption B: 53	LLW: 160 HLW Suboption A: 85 HLW Suboption B: 53	LLW: 160	TRUW: 55, 160 LLW: 160 HLW Suboption A: 85 HLW Suboption B: 53	
6 Noncombustible waste forms	Same as Option 4	Same as Option 4	Shred in either CH or RH shredder. Burn. Cement ash, media, concentrated scrubbing solution and metals in RH in-drum mixer.	Mix with sufficient cement in in-drum mixer for LLW	Treat noncombustibles as failed equipment. Burn all combustibles. Cement ash and scrubber solution.	Option objective: no combustibles to the repository
Container size, gal	TRU: 160	TRU: 160	TRU: 55	LLW: 160	TRU: 55, 160	

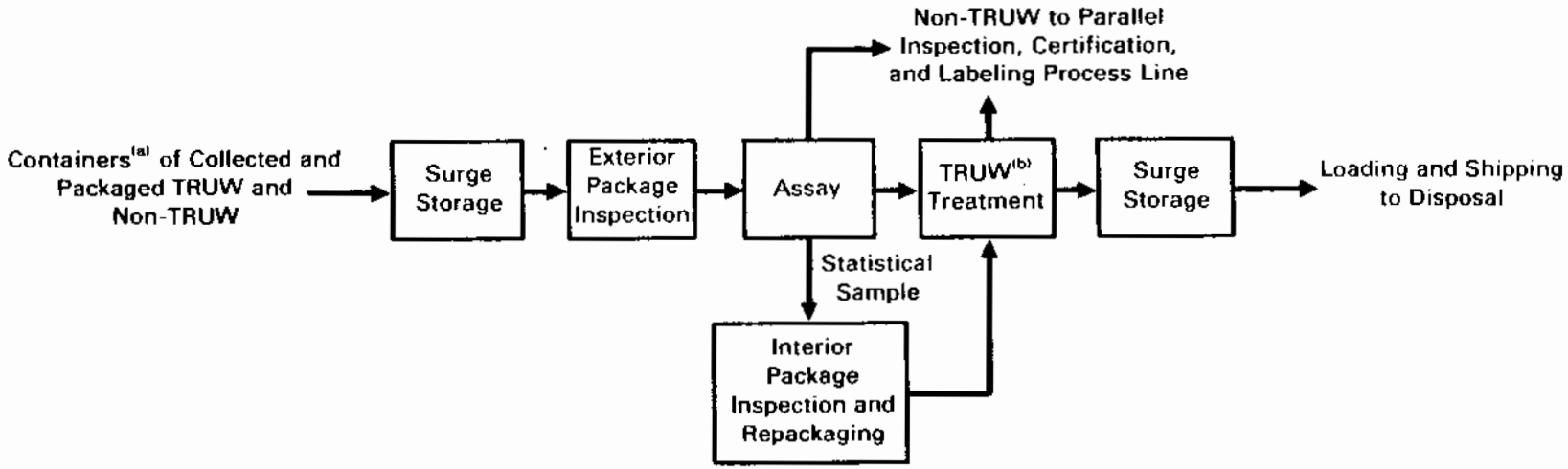

FIGURE 7.1. Process Flow Diagram for TRUW Treatment[b]

(a) These containers are from a reprocessing facility.
(b) The process flow diagram for the six TRUW treatment options studied is depicted in Figures 7.2, 7.3, 7.4, 7.5, 7.6, and 7.7. Any inspection, sampling, certification, or labeling steps of the processed TRUW are shown as part of the TRUW treatment option.

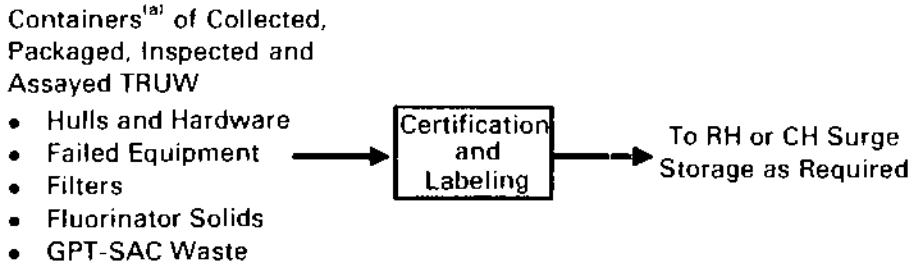

FIGURE 7.2. Process Flow Diagram for Option 1 - No Treatment[b]

(a) These containers hold the inspected and assayed TRUW collected and packaged at the reprocessing facility, as depicted in Figure 7.1.
(b) Process steps prior to and following the above process step are depicted in Figure 7.1.

canister information based on reprocessing 1,500 MTU/yr. The data are based on values given in Section 5.

7.2 OPTION 2 - MINIMUM TREATMENT (compaction)

The minimum treatment option involves physical compaction of the wastes. This treatment option assumes that some compaction can be attained for all of the waste types except fluorinator solids. (See Appendix B for bases of the compaction factors.) The compaction factors were estimated for each type of waste and were defined as the net (unpackaged) volume divided by the final compacted volume (before packaging). A compaction factor of 3.3 was assumed for the hulls and hardware. A compaction factor of 4 was assumed for the fraction of waste that Darr (1983) defined as being compactible, and a factor of 1.67 was assumed for the noncompactible fraction. Size reduction prior to compaction is required in some cases to ensure that the pieces will fit into the compactor. All the compacted waste is packaged at 90 vol% and loaded in 160-gal containers. Since it is assumed that essentially no compaction could be attained with the fluorinator solids, they are retained in their original containers.

The compaction will increase the volumetric concentration of the radionuclides. Therefore some of the waste that was originally CH may become RH after compaction. Simplified calculations of dose rates were performed to

TABLE 7.2. Weights, Volumes, and Containers of TRUW from Option 1 - No Treatment

Waste Type	CH/RH	Amounts/yr for 1,500 MTU/yr Reprocessed[a,b] Net Weight and Volume, kg	Net Weight and Volume, m^3	Packaged Volume, m^3	Nominal Container Size, L	Nominal Container Size, gal	Number of Containers
Hulls and hardware	RH	486,000	637.1	681.3	2,270	600	300
Failed equipment	CH	17,600	19.8	23.6	210	55	70
					2,270	600	4
	RH	3,600	6.2	9.1	2,270	600	4
Filters	CH	16,380	117.6	347.9	210	55	50
					300	80	1,114
	RH	3,710	30.3	140.2	300	80	133
					2,270	600	44
Fluorinator solids	RH	30,970	17.5	19.3	210	55	93
GPT-SAC waste	CH	11,340	104	112.3	210	55	540
	RH	7,080	70.3	125.2	210	55	198
					2,270	600	37
Total containers	CH					55	660
						80	1,114
						600	4
	RH					55	291
						80	133
						600	385

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of calculations.
(b) 657.9 containers/yr of 200-L HLW containers are not shown.

estimate the new dose rate range of the compacted waste. It was assumed that surface dose rate increases linearly with waste concentration, that it is a weak function of increased canister size, and that compaction provides negligible additional self-shielding.

The process and equipment flow diagram for this option is shown in Figure 7.3. TRUW is first sorted and separated into CH TRUW and RH TRUW, and these streams are then sorted by size. The large pieces of failed equipment, filters, and GPT-SAC waste are segregated, size reduced, and placed into 160-gal canisters with the smaller pieces of these wastes. This waste and the hulls and hardware are compacted in campaigns of CH or RH waste in a single in-can compactor. A lid is sealed onto the canister after it is filled. All sealed canisters are inspected, assayed, certified, and labeled prior to being transferred to surge storage. Process steps prior to and following those shown in Figure 7.3 are shown in Figure 7.1.

The treated and packaged weights and volumes and canister information for this option are given in Table 7.3 (based on a reprocessing rate of 1,500 MTU/yr). See Appendix B for discussion of the derivation of these values. This option reduces the waste volume (based on the packaged volume in Option 1) by a factor of about 4.

7.3 OPTION 3 - MINIMUM NUMBER OF PROCESSES AND PRODUCTS (cementing)

In this option, all the wastes (with size reduction or shredding for some wastes) are immobilized in cement and packaged at 90 vol% waste loading. Figure 7.4 depicts the process and equipment flow diagram. Process steps prior to and following those shown in Figure 7.4 are given in Figure 7.1.

The hulls and hardware are removed from their original (stainless steel) 600-gal containers, mixed with cement grout, and then poured back into carbon steel 600-gal containers. The cement grout increases the hulls and hardware volume by an estimated 10 vol%. The failed equipment is size reduced as necessary, and then premixed cement grout is poured over it in a carbon steel container of the same size as the original stainless steel container. The cement is assumed to fill the existing voids in the failed equipment containers with no increase in packaged waste volume. One RH cement mixer is dedicated to cementing the hulls, hardware, and failed equipment. The cement is also assumed to reduce the surface dose rate of the cortainers by a factor of 4, thus converting some of the failed equipment from RH to CH after cementing.

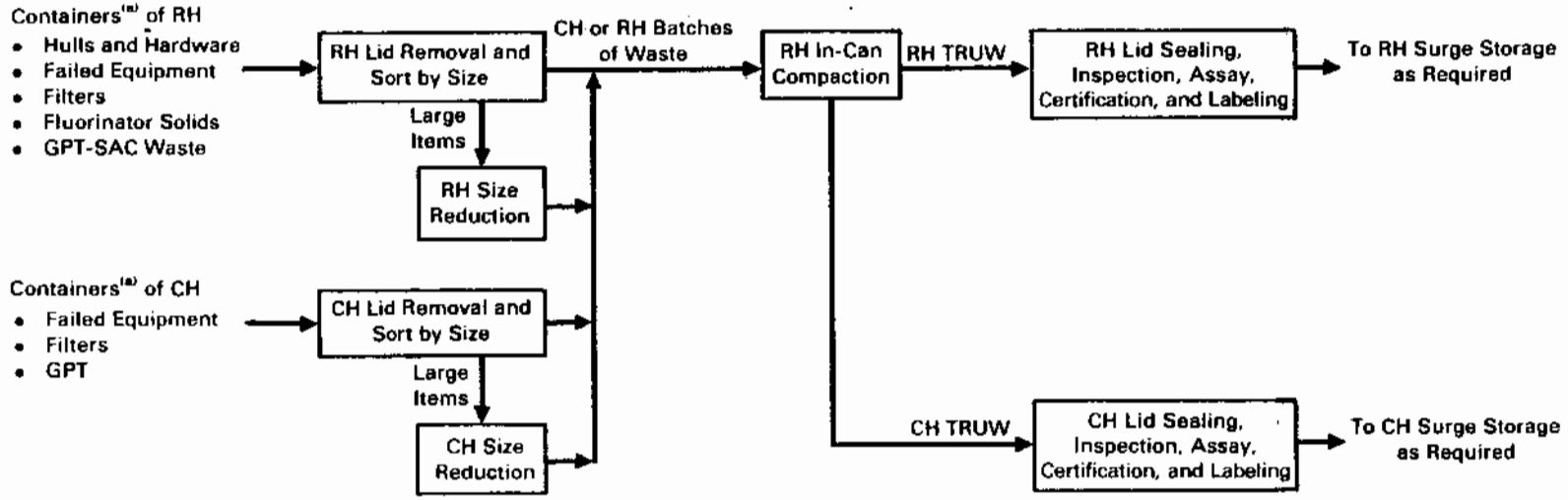

FIGURE 7.3. Process and Equipment Flow Diagram for Option 2 - Minimum Treatment[b]

(a) These containers hold the TRUW collected and packaged at the reprocessing facility that has been inspected and assayed, as depicted in Figure 7.1.

(b) This is the flow diagram representing the minimum treatment option for the block titled "TRUW Treatment" in Figure 7.1. Process steps prior to and following the above process steps are also depicted there.

TABLE 7.3. Weights, Volumes, and Containers of Treated TRUW from Option 2 - Minimum Treatment

Waste Type	CH/RH	Amounts/yr for 1,500 MTU/yr Reprocessed[a,b]: Net Weight, kg	Packaged Volume, m^3	Nominal Container Size, L	Nominal Container Size, gal	Number of Containers
Hulls and hardware	RH	486,000	212.6	610	160	350.5
Failed equipment	CH	17,600	13.2	610	160	21.8
	RH	3,600	4.2	610	160	6.9
Filters	CH	9,040	16.9	610	160	27.9
	RH	11,050	24.2	610	160	39.9
Fluorinator solids	RH	30,970	19.3	210	55	93
GPT-SAC waste	CH	7,980	25.1	610	160	41.5
	RH	10,440	39.3	610	160	64.8
Total containers	CH				160	91.2
	RH				55	93
					160	462.1

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) 657.9 containers/yr of 200-L HLW containers are not shown.

The filters and GPT-SAC wastes are shredded in the appropriate RH or CH shredder. RH and CH batches of shredded waste are then mixed with the fluorinator solids and cement in an RH in-drum cementation facility. A key assumption that a maximum of 40 kg of "soft" material (cellulose, plastic and rubber, filter media) and 60 kg of "hard" material can be included in the cement formulation is taken from Schneider and Ledebrink (1983). The final reference cement formulation (60 kg of hard material and 40 kg of soft material, plus cement and water) yields 0.20 m^3 of cemented waste. (The amount of combustibles in this cement formulation is within the limits of the WIPP criteria, although WIPP criteria are not necessarily the same as those for commercial TRUW; see Table 4.1.) Aluminum in the filters can cause problems

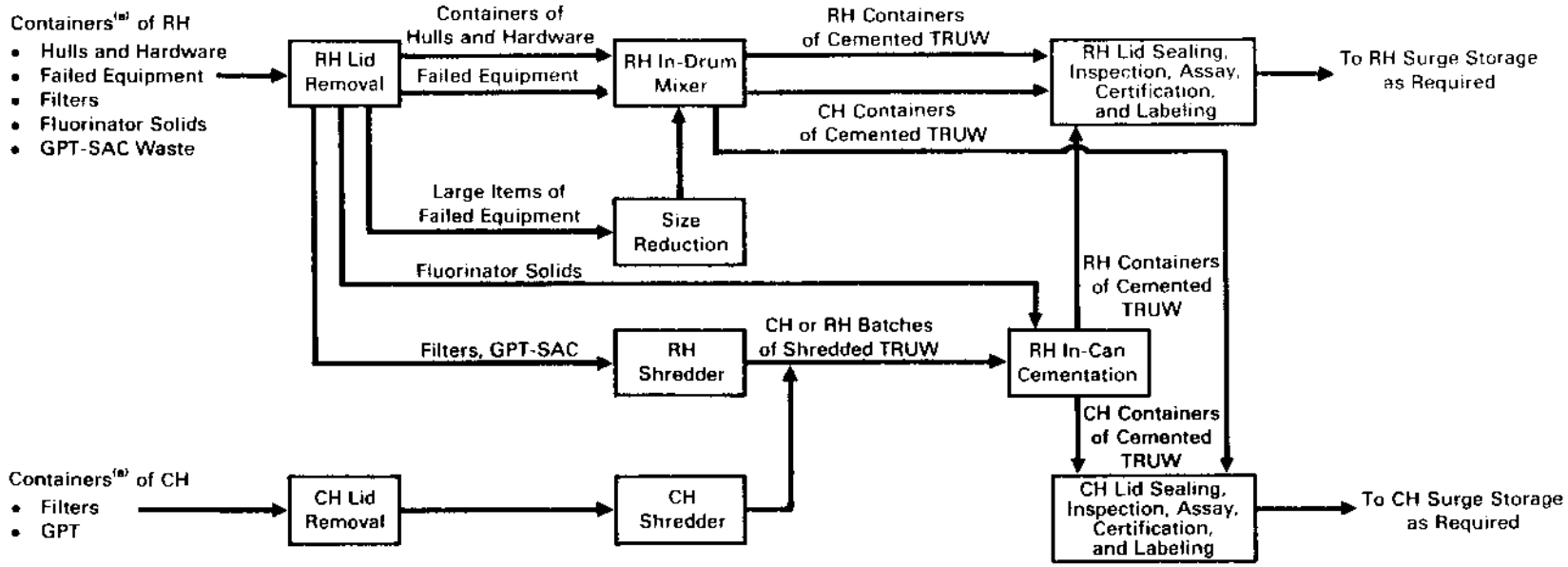

FIGURE 7.4. Process and Equipment Flow Diagram for Option 3 - Minimum Number of Processes and Products[b]

(a) These containers hold the TRUW collected and packaged at the reprocessing facility that has been inspected and assayed, as depicted in Figure 7.1.

(b) This is the flow diagram representing Option 3 for the block titled "TRUW Treatment" in Figure 7.1. Process steps prior to and following the above process steps are also depicted there.

because it can react with the alkaline cement to form aluminum hydroxide and produce hydrogen gas. Because there is less void space to fill with cement in the shredded filters and GPT-SAC waste than in the failed equipment, it was assumed that cementation would provide more shielding for the filters and GPT-SAC waste than for the failed equipment. Therefore, the cementing is assumed to reduce the surface dose rate of the filters and GPT-SAC waste by a factor of 2. The cemented filters are packaged in 55-gal drums.

The fairly high gamma content of the fluorinator solids will cause some of the CH filters and CH GPT to become RH after being cemented with the fluorinator solids; this is accounted for in the surface dose rate estimate. The cemented fluorinator solids are packaged in 55-gal drums.

The net weight and packaged volumes of waste and canister information for Option 3 are given in Table 7.4. This option reduces the waste volume (based on the packaged volume in Option 1) by a factor of about 1.1.

TABLE 7.4. Weights, Volumes, and Containers of Treated TRUW from Option 3 - Minimum Number of Processes and Products

	Amounts/yr for 1,500 MTU/yr Reprocessed[a,b]					
		Net	Packaged	Nominal Container Size		
Waste Type[c]	CH/RH	Weight, kg	Volume, m^3	L	gal	Number of Containers
Hulls and hardware	RH	1,893,600	779	2,270	600	343
Failed equipment	CH	59,260	26.0	210	55	70
	RH	15,560	6.8	2,270	600	8
Filters	CH	49,140	27.3	210	55	131.4
	RH	48,240	26.7	210	55	128.6
GPT-SAC waste	CH	63,900	35.5	210	55	170.5
	RH	77,580	43.1	210	55	207.5
Total containers	CH				55	371.9
	RH				55	336.1
					600	351

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) 657.9 containers/yr of 200-L HLW containers are not shown.
(c) Fluorinator solids are included in Filters and GPT-SAC Waste totals.

7.4 OPTION 4 - MAXIMUM VOLUME REDUCTION WITHOUT DECONTAMINATION (melting)

High volume reduction factors are attained by burning the combustibles (excluding plastic and rubber), melting the metals and incineration residues, and hot pressing the plastic and rubber. All the treated waste is packaged at 90 vol% loading in 160-gal canisters. Process steps prior to and following those in Figure 7.5 are given in Figure 7.1.

After prior size reduction of some of the failed equipment and fuel assembly hardware, these two waste types are melted in CH or RH batches in a single RH vacuum induction melter (Montgomery and Nesbitt 1983) to 90% of theoretical density.

The filters are shredded in either a CH or RH shredder and incinerated in an RH incinerator, resulting in an RH mixture of ash, media, and metals. The metals are then removed and combined with the failed equipment for melting as RH and CH. The ash, filter media, and concentrated scrubber solution residues are melted in the RH melter.

It is assumed that the CH/RH category of the metal HEPA filter frames does not change due to processing, since the melting crucible will be periodically changed and the CH melting can be done in campaigns, resulting in little cross-contamination. Other streams may change from CH to RH due to concentration by melting.

The GPT-SAC waste is sorted into metals, plastic and rubber, and cellulose (i.e., paper, rags). The metals are melted with the failed equipment in CH and RH campaigns. The cellulose is incinerated with the filters previously mentioned, and the ash and scrubber residues from this incineration are melted as RH waste. To avoid large quantities of chlorine in the scrubber solution (from incineration of PVC plastics), the CH or RH batches of plastic and rubber are pressed in collapsible cans in an RH hot press. The compressed cans are then placed in the final container. Remote handled batches of fluorinator solids are melted to 90% of their theoretical density.

The packaged and unpackaged weights and volumes and container information for this option are given in Table 7.5. This option reduces the original volume of waste (based on packaged volume of untreated waste) by a factor of 12.5.

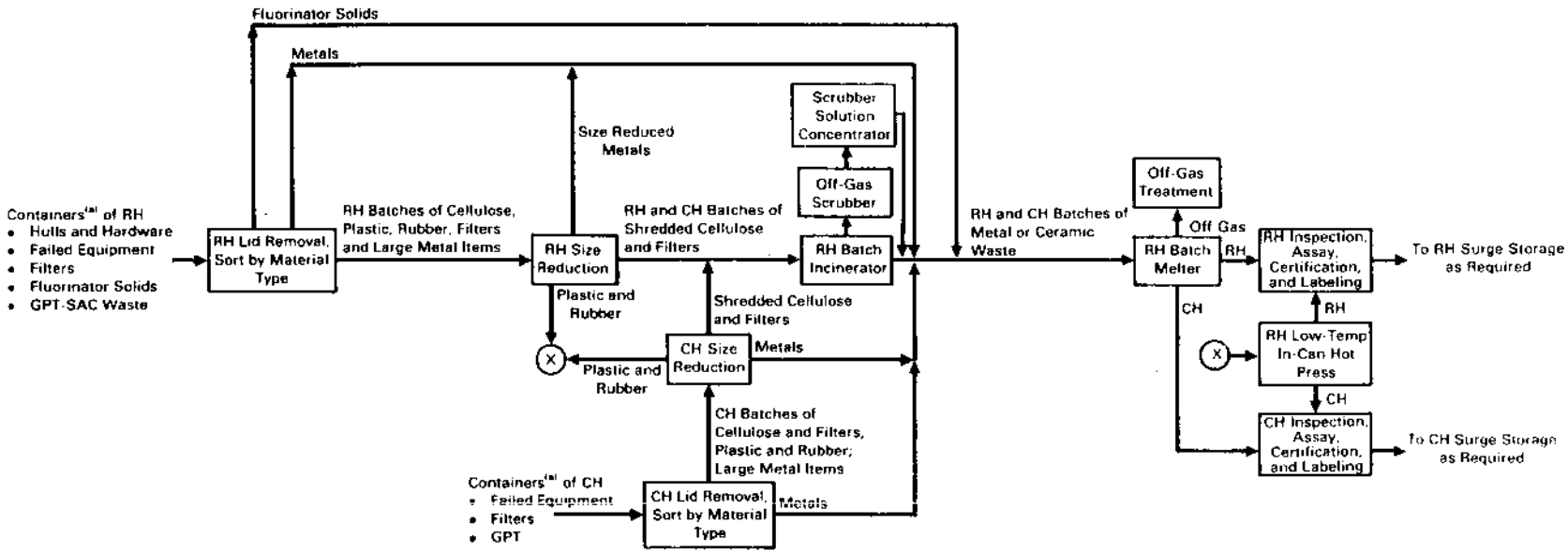

FIGURE 7.5. Equipment and Process Flow Diagram for Option 4 - Maximum Volume Reduction Without Decontamination[b]

(a) These containers hold the TRUW collected and packaged at the reprocessing facility that has been inspected and assayed, as depicted in Figure 7.1.

(b) This is the flow diagram representing Option 4 for the block titled "TRUW Treatment" in Figure 7.1. Process steps prior to and following the above process steps are also depicted there.

TABLE 7.5. Weights, Volumes, and Containers of Treated TRUW from Option 4 - Maximum Volume Reduction Without Decontamination

Waste Type	CH/RH	Amounts/yr for 1,500 MTU/yr Reprocessed[a,b] Net Weight, kg	Packaged Volume, m^3	Nominal Can Size L	Nominal Can Size gal	Number of Containers
Hulls and hardware	RH	486,000	92.3	610	160	152.3
Failed equipment	CH	17,600	2.8	610	160	4.6
	RH	3,600	0.6	610	160	0.9
Filters	CH	7,740	2.4	610	160	3.9
	RH	4,800	2.2	610	160	3.7
Fluorinator solids	RH	30,970	9.4	610	160	15.5
GPT-SAC waste	CH	2,710	2.2	610	160	3.7
	RH	6,770	3.4	610	160	5.6
Total containers	CH				160	12.2
	RH				160	178.0

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) 657.9 containers/yr of 200-L HLW containers are not shown.

7.5 OPTION 5 - MAXIMUM VOLUME REDUCTION WITH DECONTAMINATION

In this option, the decontaminable metal, plastic, and rubber are decontaminated, and the nondecontaminable metals are compacted. The cellulose and filters are incinerated, and following incineration, the metal filter frames are removed and decontaminated with the failed equipment. The residues from the incineration are vitrified with the HLW. The process and equipment flow diagram is given in Figure 7.6, and process steps prior to and following those in Figure 7.6 are shown in Figure 7.1.

The hulls are cryogenically cooled so that they can be cracked to break open and size reduce the cylindrical hull pieces, and then they are decontaminated in a device called a centrifugal barrel. Two suboptions are considered for treating the resulting decontamination slurry, assumed to contain zirconium, zirconium dioxide, and aluminum oxide. In Suboption 5A, the

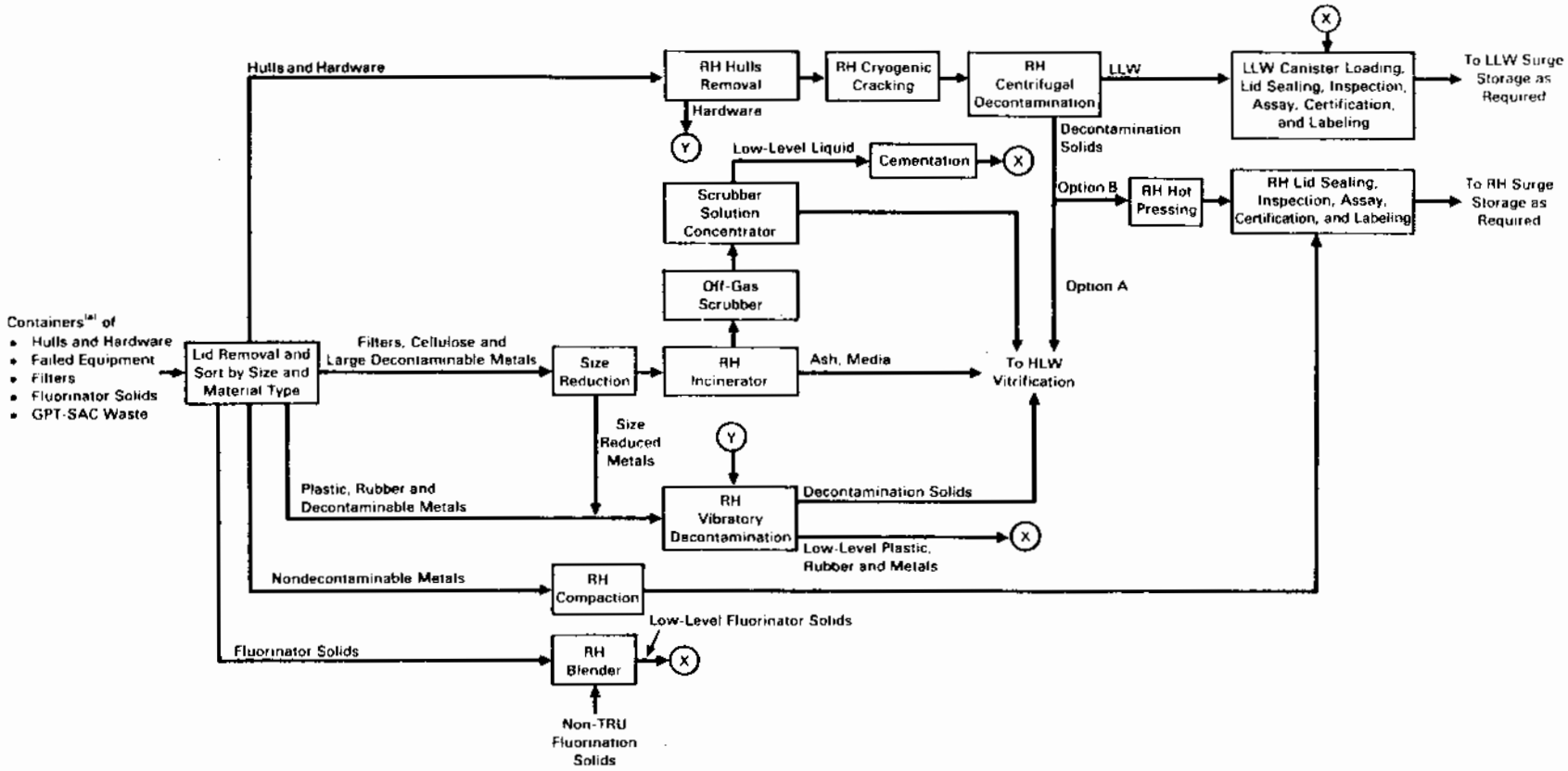

FIGURE 7.6. Process and Equipment Flow Diagram for Option 5 - Maximum Volume Reduction with Decontamination[b]

(a) These containers hold the TRUW collected and packaged at the reprocessing facility that has been inspected and assayed, as depicted in Figure 7.1.

(b) This is the flow diagram representing Option 5 for the block titled "TRUW Treatment" in Figure 7.1. Process steps prior to and following the above process steps are also depicted there.

zirconium, zirconium dioxide, and aluminum oxide are combined with the HLW glass at 20 wt% equivalent waste loading. The diameter of the HLW canisters from the reprocessing operation is increased so that the additional HLW from the TRUW treatment can be accommodated in the same number of HLW containers. This was done because canister contents can be limited during storage, transportation, and disposal by total heat generation rate, which is not significantly changed by the addition of the TRUW. In Suboption 5B the decontamination slurry is hot pressed to a density of 3,510 kg/m^3 (90% of theoretical density) to become RH TRUW. A preoxidation step to convert zirconium to zirconium dioxide may be required.

The hardware from the spent fuel, decontaminable failed equipment and metallic GPT-SAC waste, and plastic and rubber are decontaminated by vibratory finishing. The decontamination slurry (consisting of metal, plastic, and rubber fines), incineration ash, and sodium hydroxide (from the incinerator off-gas scrubber) are vitrified at 33 wt% loading with the HLW glass.

The combustible parts of the filters and cellulose GPT-SAC waste are incinerated. The metal in the filters is removed and decontaminated by vibratory finishing with the metals mentioned above. The ash and scrubber residues are loaded into the HLW glass at 33 wt% and the filter media at 100 wt%. The small quantity of chlorine in the plastic and rubber fines from the GPT-SAC incineration could present volatilization and off-gas difficulties when treated by vitrification.

The TRU fluorinator solids are reduced to LLW by mixing them with the other non-TRU fluorinator solids. This strategy will require good radiological characterization of each batch of waste.

The packaged weights and volumes and container information for the decontamination option based on 1,500 MTU are given in Table 7.6 for Suboption 5A and in Table 7.7 for Suboption 5B.

TABLE 7.6. Weights, Volumes, and Containers of Treated TRUW from Suboption 5A - Maximum Volume Reduction with Decontamination (vitrification with HLW glass)[a]

Waste Type	LLW/HLW CH TRUW RH TRUW	Amount/yr for 1,500 MTU/yr Reprocessed[a] Net Weight, kg	Packaged Volume, m^3	Nominal Container Size L	Nominal Container Size gal	Number of Containers
Hulls	LLW	373,380	305.0	610	160	503.3
	HLW	183,260	75.4	320	85	(b)
Hardware	LLW	84,350	93.7	610	160	154.6
	HLW	730	0.3	320	85	(b)
Failed equipment	LLW	14,810	10.1	610	160	16.7
	HLW	129	0.05	320	85	N/A
	CH TRUW	4,831	4.0	610	160	6.5
	RH TRUW	1,529	1.3	610	160	2.1
Filters	LLW	10,340	21.7	610	160	35.8
	HLW	8,450	3.2	320	85	(b)
Fluorinator solids	LLW	--	20.6	610	160	32.0
GPT-SAC waste	LLW	7,460	78.9	610	160	130.2
	HLW	760	0.3	320	85	(b)
	CH TRUW	506	0.4	610	160	0.7
	RH TRUW	19,550	11.9	210	55	57.4
		780	0.6	610	160	1.1
Total containers and HLW volume	LLW				160	874.6
	HLW		79.3		85	(b)
	CH TRUW				160	7.2
	RH TRUW				55	57.4
				160	3.2	

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

(b) The HLW generated resulting from TRUW processing is combined with the original HLW generated from the 1,500 MTU/yr reprocessing. The size of the original HLW canister is increased (from 12.3 in. i.d. by 120 in. long to 15.5 in. i.d. by 120 in. long) to accommodate this additional waste. Therefore the original number of HLW canisters (657.9) does not change.

TABLE 7.7. Weights, Volumes, and Containers of Treated TRUW from Suboption 5B - Maximum Volume Reduction with Decontamination (hot pressing with solids to become RH TRUW)[a]

Waste Type	LLW/HLW CH TRUW RH TRUW	Amounts/yr for 1,500 MTU/yr Reprocessed[a] Net Weight, kg	Packaged Volume, m^3	Nominal Container Size L	Nominal Container Size gal	Number of Containers
Hulls	LLW	373,380	305	610	160	503.3
	RH TRUW	33,033	9.2	610	160	15.2
Hardware	LLW	84,350	93.7	610	160	154.6[b]
	HLW	730	0.3	200	53	
Failed equipment	LLW	14,810	10.1	610	160	16.7[b]
	HLW	129	0.05	200	53	
	CH TRUW	4,831	4.0	610	160	6.5
	RH TRUW	1,529	1.3	610	160	2.1
Filters	LLW	10,340	21.7	610	160	35.8[b]
	HLW	8,450	3.2	200	53	
Fluorinator solids	LLW	30,970	19.4	610	160	32.0
GPT-SAC waste	LLW	7,460	78.9	610	160	130.2[b]
	HLW	760	0.3	200	53	
	CH TRUW	506	0.4	610	160	0.7
	RH TRUW	19,550	11.9	210	55	57.4
		780	0.6	610	160	1.1
Total containers and HLW volume	LLW				160	874.6[b]
	HLW		3.8		53	
	CH TRUW				160	7.2
	RH TRUW				55	57.4
				160	18.4	

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

(b) The HLW generated resulting from TRUW processing is combined with the original HLW generated from the 1,500 MTU/yr reprocessing. It is assumed that the 3.8 m^3 of HLW generated from the TRUW processing can be added to the HLW from the reprocessing without increasing the number of canisters or requiring that the canister size (12.3 in. i.d. x 120 in. long) be increased.

7.6 OPTION 6 - NONCOMBUSTIBLE FORMS (melting and cementing)

The noncombustible waste form option involves melting most of the metals, shredding and burning the filters and the combustible parts of GPT-SAC waste (the metals in the GPT-SAC waste are removed prior to incineration and melted with the failed equipment), and cementing the ash and secondary wastes from incineration and fluorinator solids. This option is very similar to Option 4; the major differences are that the filters are cemented following incineration, the fluorinator solids are cemented, the plastic and rubber from the GPT-SAC waste are incinerated with the cellulose, and the scrubber solution residues from incineration are cemented. The process and equipment flow diagram is given in Figure 7.7. Process steps prior to and following those in Figure 7.7 are shown in Figure 7.1.

The hulls and hardware, failed equipment, and the metals from the GPT-SAC waste are melted in the same manner as the metals in Option 4.

The filters and combustible GPT-SAC wastes are shredded in either a RH or CH shredder and are then incinerated in CH or RH batches in the same incinerator. CH and RH batches of ash, scrubber residues, media, and metal frames are cemented in their respective batches in a single RH in-drum mixer, using the same cement recipe as in Option 3. The fluorinator solids are cemented at 30 wt%, which results in LLW. The cemented waste is loaded at 90 vol%. The packaged weights and volumes and container information for the noncombustible waste forms option are given in Table 7.8.

7.7 SUMMARY OF WASTE QUANTITIES

Table 7.9 summarizes the initial and final volumes of packaged waste in each treatment option. Also included in this table are the volume reduction ratios, obtained by dividing the no treatment packaged volumes by the final packaged volumes in each treatment option.

In Options 2, 4 and 6, volume reductions are achieved by concentrating the initial TRUW into a smaller volume by compaction, melting, or incineration and

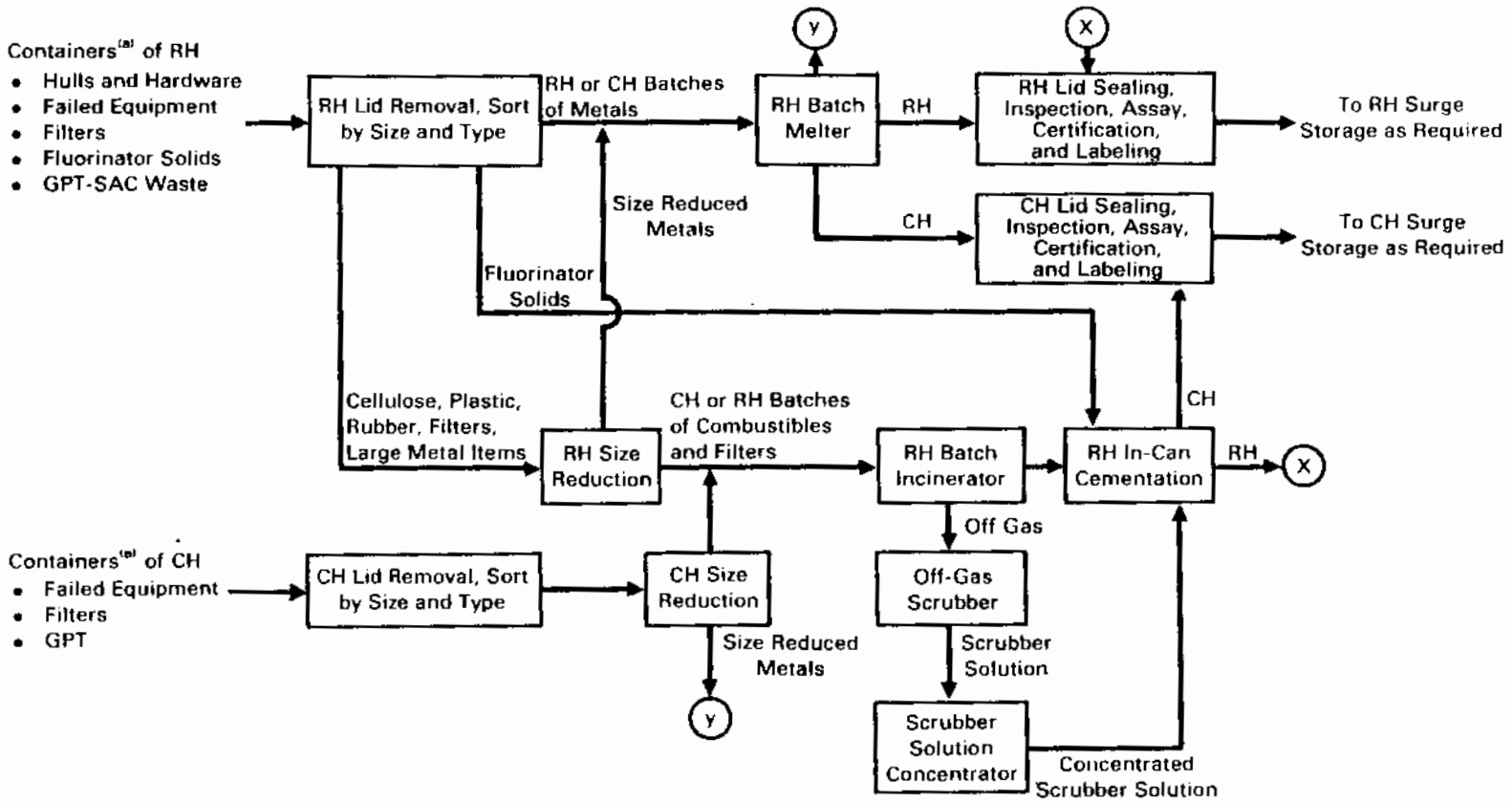

FIGURE 7.7. Process and Equipment Flow Diagram for Option 6 - Noncombustible Waste Forms[b]

(a) These containers hold the TRUW collected and packaged at the reprocessing facility that have been inspected and assayed, as depicted in Figure 7.1.
(b) This is the flow diagram representing Option 6 for the block titled "TRUW Treatment" in Figure 7.1. Process steps prior to and following the above process steps are also depicted there.

TABLE 7.8. Weights, Volumes, and Containers of Treated TRUW from Option 6 - Noncombustible Waste Forms

Waste Type	LLW/HLW CH TRUW RH TRUW	Amount/yr for 1,500 MTU/yr Reprocessed[a] Net Weight, kg	Packaged Volume, m^3	Nominal Container Size L	Nominal Container Size gal	Number of Containers
Hulls and hardware	RH TRUW	486,000	92.3	610	160	152.3
Failed equipment	CH TRUW	17,600	2.8	610	160	4.6
	RH TRUW	3,600	0.6	610	160	1.0
Filters	CH TRUW	47,230	23.6	210	55	113.5
	RH TRUW	30,410	15.2	210	55	73.2
Fluorinator solids	LLW	30,970	57.4	610	160	94.6
GPT-SAC waste	CH TRUW	2,560	1.3	210	55	6.2
		1,220	0.2	610	160	0.3
	RH TRUW	4,410	2.4	210	55	11.7
		3,950	0.5	610	160	0.8
Total containers	LLW				160	94.6
	CH TRUW				55	119.7
					160	4.9
	RH TRUW				55	84.9
					160	154.1

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) 657.9 containers/yr of 200-L HLW containers are not shown.

melting. This causes some of the wastes which are initially CH TRUW to become RH TRUW; this in turn causes the high volume reduction ratios for CH TRUW in Options 2 and 4. Therefore the CH TRUW is not only volume reduced, but the actual quantity of CH TRUW is also reduced.

In Option 6, cementing is also employed, which provides some shielding, so some of the RH TRUW becomes CH TRUW. Thus in Options 3 and 6, the volume reduction ratios for CH TRUW are not very high because some of the RH TRUW has been reclassified as CH TRUW.

Option		Bulls and Hardware Packaged Volume, m^3			Failed Equipment Packaged Volume, m^3			Filters Packaged Volume, m^3			Fluorinator Solids Packaged Volume, m^3			GPT-SAC Waste Packaged Volume, m^3			Total 1,500 MTU Packaged Volume, m^3			Total 70,000 MTU Basis Packaged Volume, m^3	
	RH TRUW CH TRUW LLW/HLW	V_o	V_f	V_o/V_f[b]	V_o	V_f	V_o/V_f[b]	V_o	V_f	V_o/V_f[b]	V_o	V_f	V_o/V_f[b]	V_o	V_f	V_o/V_f[b]	V_o	V_f	V_o/V_f[b]	V_o	V_f
1. No treatment	CH TRUW	0	0	0	23.6	23.6	1.0	347.9	347.9	1.0	0	0	0	112.3	112.3	1.0	483.8	483.8	1.0	22,580	22,580
	RH TRUW	681.3	681.3	1.0	9.1	9.1	1.0	140.2	140.2	1.0	19.4	19.4	1.0	125.2	125.2	1.0	975.1	975.1	1.0	45,500	45,500
2. Minimum treatment	CH TRUW	0	0	0	23.6	13.2	1.8	347.9	16.9	20.6	0	0	0	112.3	25.1	4.5	483.8	55.2	8.8	22,580	2,580
	RH TRUW	681.3	212.6	3.2	9.1	4.2	2.2	140.2	24.2	5.8	19.4	19.4	1.0	125.2	39.3	3.2	975.1	299.6	3.3	45,500	13,980
3. Minimum number of processes and products	CH TRUW	0	0	0	23.6	26.0	0.9	347.9	27.3	12.7	0	0	0	112.3	35.5	3.2	483.8	88.8	5.4	22,580	22,580
	RH TRUW	681.3	779.0	0.9	9.1	6.8	1.3	140.2	26.8	5.3	19.4	0	N/A	125.2	43.1	2.9	975.1	855.7	1.1	45,500	39,930
4. Maximum volume reduction without decontamination	CH TRUW	0	0	0	23.6	2.8	8.4	347.9	2.4	145	0	0	0	112.3	2.2	51	483.8	7.4	65.0	22,580	340
	RH TRUW	681.3	92.3	7.4	9.1	0.6	15.0	140.2	2.2	64	19.4	9.4	2.1	125.2	3.4	37	975.1	107.9	9.0	45,500	5,040
5A. Maximum volume reduction with decontamination	CH TRUW	0	0	0	23.6	4.0	5.9	347.9	0	N/A	0	0	0	112.3	0.4	281.0	483.8	4.4	110.0	22,580	200
	RH TRUW	681.3	0	N/A	9.1	1.3	7.0	140.2	0	N/A	19.4	0	N/A	125.2	12.5	10.0	975.1	13.8	71.0	45,500	640
	LLW[c]	0	398.7	N/A	0	10.1	N/A	N/A	21.7	N/A	0	19.4	N/A	0	78.9	N/A	0	528.8	0	0	24,880
	HLW[c]	0	75.7	N/A	0	0.05	N/A	N/A	3.2	N/A	0	0	0	0	0.3	N/A	0	79.2	0	0	3,700
5B. Maximum volume reduction with decontamination	CH TRUW	0	0	0	23.6	4.0	N/A	347.9	0	N/A	0	0	0	112.3	0.4	281.0	483.8	4.4	110.0	22,580	200
	RH TRUW	681.3	9.2	74.0	9.1	1.3	N/A	140.2	0	N/A	19.4	0	N/A	125.2	12.5	10.0	975.1	23.0	42.0	45,500	1,090
	LLW[c]	0	398.7	N/A	0	10.1	0	0	21.7	0	0	19.4	0	0	78.9	0	0	528.8	0	0	24,680
	HLW[c]	0	0.3	N/A	0	0.05	0	0	3.2	0	0	0	0	0	0.3	0	0	3.8	N/A	0	180
6. Noncombustible waste forms	CH TRUW	0	0	0	23.6	2.8	8.4	347.9	23.6	15.0	0	0	0	112.3	1.5	75.0	483.8	27.9	17.0	22,580	1,300
	RH TRUW	681.3	92.3	7.4	9.1	0.6	15.0	140.2	15.2	9.2	19.4	0	N/A	125.2	2.9	43.0	975.1	111.0	8.8	45,500	5,180
	LLW[c]	0	0	0	0	0	0	0	0	0	0	57.4	N/A	0	0	0	0	57.4	N/A	0	2,680

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

(b) V_o/V_f is defined as initial packaged volume divided by the final packaged volume. If the final packaged volume is zero with a finite initial packaged volume, this implies that the waste type was converted to another waste form resulting in $V_o/0$, or infinity. If the initial packaged volume is zero with a finite final volume, then a waste form was created, or $0/V_f$. In both of these cases, "Nonapplicable" (N/A) is indicated under V_o/V_f.

TABLE 7.9. Initial and Final Volumes from Packaged Waste of Each TRUW Waste Treatment Option[a]

The volume reduction ratios in Option 5 do not describe the change in waste volume very effectively, since much of the original TRUW is not processed into another form of TRUW but instead is decontaminated to produce LLW and HLW (in Suboption 5A) or decontaminated to produce LLW and TRUW (in Suboption 5B). Thus the significant reduction in the quantity of TRUW in these subsections is somewhat misleading, since most of the TRUW is converted to HLW or LLW.

The greatest volume reduction ratios are attained in Option 4 (volume reduction ratios are 66.0 for CH TRUW and 9.0 for RH TRUW) and in Option 6 (volume reduction ratios are 17.3 for CH TRUW, 8.8 for RH TRUW, plus 57.3 m^3 of LLW that cannot be included in the volume reduction ratio because there is no LLW in Option 1 with which to compare it).

Table 7.10 summarizes the final number of containers holding treated TRUW, the increase in the number of cans of LLW, and the increase in volume of HLW.

7.8 REFERENCES

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

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

Schneider, V. W., and F. W. Ledebrink. 1983. "Cementation of TRU-Wastes by a New Process, Properties of the Products." Presented at Second International Symposium on Ceramics in Nuclear Waste Management, Chicago, Illinois.

Option	RH TRUW / CH TRUW / LLW/HLW	Hulls and Hardware: Number of Cans, Can Size, gal 160	600	HLW Volume, m^3	Failed Equipment: Number of Cans, Can Size, gal 55	160	600	HLW Volume, m^3	Filters: Number of Cans, Can Size, gal 55	80	160	600	HLW Volume, m^3	Fluorinator Solids: Number of Cans, Can Size, gal 55	160	GPT-SAC Waste: Number of Cans, Can Size, gal 55	160	600	HLW Volume, m^3	Total 1500 MTU Basis: Number of Cans, Can Size, gal 55	80	160	600	HLW Volume, m^3	Total 70,000 MTU Basis: Number of Cans x 1,000, Can Size, gal 55	80	160	600	HLW Volume, m^3
1. No treatment	CH TRUW	0	300	N/A[b]	70	0	4	N/A	50	1,114	0	0	N/A	0	0	540	0	0	N/A	660	1,114	0	4	N/A	30.8	52.0	0	0.2	N/A
	RH TRUW	0	0	N/A	0	0	4	N/A	0	133	0	44	N/A	93	0	198	0	37	N/A	291	133	0	385	N/A	13.6	6.2	0	18.0	N/A
2. Minimum treatment	CH TRUW	0	0	N/A	0	21.8	0	N/A	0	0	27.9	0	N/A	0	0	0	41.5	0	N/A	0	0	91.2	0	N/A	0	0	4.3	0	N/A
	RH TRUW	350.5	0	N/A	0	6.9	0	N/A	0	0	39.9	0	N/A	93	0	0	64.8	0	N/A	93	0	462.1	0	N/A	4.3	0	21.6	0	N/A
3. Minimum number of processes and products	CH TRUW	0	0	N/A	70	0	0	N/A	131.4	0	0	0	N/A	0[c]	0	170.5	0	0	N/A	371.9	0	0	0	N/A	17.4	0	0	0	N/A
	RH TRUW	0	343	N/A	0	0	8	N/A	128.6	0	0	0	N/A	0[c]	0	207.5	0	0	N/A	336.1	0	0	351	N/A	15.7	0	0	16.4	N/A
4. Maximum volume reduction without decontamination	CH TRUW	0	0	N/A	0	4.6	0	N/A	0	0	3.9	0	N/A	0	0	0	3.7	0	N/A	0	0	12.2	0	N/A	0	0	0.6	0	N/A
	RH TRUW	152.3	0	N/A	0	0.9	0	N/A	0	0	3.7	0	N/A	0	15.5	0	5.6	0	N/A	0	0	178	0	N/A	0	0	8.3	0	N/A
Suboption A																													
5. Maximum volume reduction with decontamination	CH TRUW	0	0	N/A	0	6.5	0	N/A	0	0	0	0	N/A	0	0	0	0.7	0	N/A	0	0	7.2	0	N/A	0	0	0.3	0	N/A
	RH TRUW	0	0	N/A	0	2.1	0	N/A	0	0	0	0	N/A	0	0	57.4	1.1	0	N/A	57.4	0	3.2	0	N/A	2.7	0	0.1	0	N/A
	LLW	657.9	0	N/A	0	16.7	0	N/A	0	0	35.8	0	N/A	0	32.0	0	130.2	0	N/A	0	0	872.6	0	N/A	0	0	40.7	0	N/A
	HLW[d]	0	0	75.7	0	0	0	0.05	0	0	0	0	3.2	0	0	0	0	0	0.3	0	0	0	0	79.2	0	0	0	0	3,694
Suboption B																													
	CH TRUW	0	0	N/A	0	6.5	0	N/A	0	0	0	0	N/A	0	0	0	0.7	0	N/A	0	0	7.2	0	N/A	0	0	0.3	0	N/A
	RH TRUW	15.2	0	N/A	0	2.1	0	N/A	0	0	0	0	N/A	0	0	57.4	1.1	0	N/A	57.4	0	18.4	0	N/A	2.7	0	0.9	0	N/A
	LLW	657.9	0	N/A	0	16.7	0	N/A	0	0	35.8	0	N/A	0	32.0	0	130.2	0	N/A	0	0	872.6	0	N/A	0	0	40.7	0	N/A
	HLW[e]	0	0	0.3	0	0	0	0.05	0	0	0	0	3.2	0	0	0	0	0	0	0.03	0	0	0	3.8	0	0	0	0	177
6. Noncombustible waste forms	CH TRUW	0	0	N/A	0	4.6	0	N/A	113.5	0	0	0	N/A	0	0	6.2	0.3	0	N/A	119.7	0	4.9	0	N/A	5.6	0	0.2	0	N/A
	RH TRUW	152.3	0	N/A	0	1.0	0	N/A	73.2	0	0	0	N/A	0	0	11.7	0.8	0	N/A	84.9	0	154.1	0	N/A	4.0	0	7.2	0	N/A
	LLW	0	0	N/A	0	0	0	N/A	0	0	0	0	N/A	0	94.6	0	0	0	N/A	0	0	94.6	0	N/A	0	0	4.4	0	N/A

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of calculations.
(b) Not applicable: the HLW volume column only applies to the volume increase of HLW resulting from the treatment option.
(c) Fluorinator solids are included in filters and GPT-SAC waste total.
(d) The HLW generated in the TRUW processing is combined with the original HLW generated from the 1,500 MTU/yr reprocessing. The diameter of the original HLW canister is increased to accommodate this additional waste. The HLW from this option is packaged in an increased diameter HLW canister with a volume of 320 L, compared to 200 L for the reference HLW canister.
(e) The HLW generated in the TRUW processing is combined with the original HLW generated from 1,500 MTU/yr reprocessing. It is assumed that the additional 3.8 m^3 of HLW generated from the TRUW processing can be added to the HLW from the reprocessing without increasing the number of canisters. The HLW from this option is packed in the 657.9 original HLW canisters with a volume of 200 L (53 gal), for a net increase of 2.8% in HLW glass volume.

TABLE 7.10. Number of Canisters/Drums Produced from Each TRUW Treatment Option[a]

8.0 COST CONSIDERATIONS

High-spot cost estimates were performed for each TRUW treatment option. The costs were estimated for constructing and operating the TRUW treatment and associated service facility beyond what currently exists at the BNFP reprocessing plant, for transporting the treated waste to a disposal site, for the disposal of the treated TRUW and incremental HLW at a repository, and for the disposal of incremental LLW at a LLW disposal site. Costs for R&D, selection and development of the repository, and decommissioning of the treatment facilities and the repository were not included. The costs presented are in mid-1983 dollars on an undiscounted basis. These estimates were used to evaluate the cost-effectiveness of the six TRUW treatment options.

This section describes the results of these cost analyses. Supporting data for the cost analyses are presented in Appendix D.

8.1 COST OF TRUW TREATMENT FACILITIES

The capital and operating costs were estimated for the TRUW treatment facilities for each strategy option studied. It was assumed that two commercial fuel reprocessing facilities would exist to supply the HLW and TRUW for a repository containing 70,000 MTU equivalent of wastes. Each reprocessing plant was assumed to have the capacity to process 1,500 MTU/yr, for a total of 35,000 MTU during its lifetime.

8.1.1 Capital Costs for TRUW Treatment Facilities

The capital costs include the cost of constructing the facility and associated service areas, and the installed cost of the equipment to process the wastes. The cost estimates for this study are based on the cost analyses from a related study (McKee et al. 1984), where applicable. When estimates were not available, they were approximated by the authors based on the costs for treatment systems in the McKee et al. (1984) study, taking into account the physical size and processing capacity of the equipment, the cell space required, and the complexity of the process.

It is assumed that a high-level liquid waste (HLLW) vitrification facility and lag storage facilities for HLW and 6 months' production of TRUW (both before and after treatment) exist for each of the strategies studied. The cost estimates reflect the fact that the post-treatment TRUW lag storage facility needs are affected by the volume reduction achieved in treating the TRUW.

The capital costs for the HLLW waste vitrification, storage, waste assay, compaction, incineration, and melting operations are taken directly from the McKee study and adjusted slightly to reflect the processing quantities used in this report. For the other operations, a consensus was reached for capital costs based on the authors' knowledge of similar operations relative to the estimates in the McKee study. Table 8.1 lists amortized capital costs based on 1,500 MTU and 70,000 MTU reprocessed for two reprocessing plants. Details of the capital costs are given in Appendix D.

The reprocessing plants and their treatment facilities are assumed to be privately owned. The amortized capital costs including an allowance for profit, taxes, and startup costs are based on a commercial facility and are assumed to be 25% of the initial total capital cost per year for the life of the plant.

TABLE 8.1. Amortized Capital Costs for the Six TRUW Treatment Options[a]

Waste Type	MTU Basis	Cost by Option, $M						
		1	2	3	4	5A	5B	6
TRUW	1,500	16.5	24.4	26.8	37.1	42.4	49.9	37.5
HLW	1,500	42.4	42.4	42.4	42.4	49.9	42.4	42.4
Total		58.9	66.8	69.2	79.5	92.3	92.3	79.9
TRUW	70,000	770	1,140	1,250	1,730	1,980	2,330	1,750
HLW	70,000	1,980	1,980	1,980	1,980	2,330	1,980	1,980
Total		2,750	3,120	3,230	3,710	4,310	4,310	3,730

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

8.1.2 Operating Costs for TRUW Treatment Facilities

The operating costs were taken from the McKee study when available. The operating costs not available in the McKee study were approximated by the authors. The operating cost was assumed to include labor, utilities, and consumable materials. The cost of purchasing containers to package the waste was estimated separately to give a total operating cost.

The operating costs available from the McKee study were adjusted to reflect the quantities of processed waste in this study. The operating costs approximated by the authors were assumed to be a fraction of the capital costs. The fractions used were derived from an analysis of the costs in DOE/ET-0028 (U.S. DOE 1979). The fractions vary somewhat, depending on the type of operation. Details of the operating costs are given in Appendix D. The operating costs for each option are given in Table 8.2.

TABLE 8.2. Operating Costs for the Six TRUW Treatment Options[a]

Waste Type	MTU Basis	Cost by Option, $M						
		1	2	3	4	5A	5B	6
TRUW	1,500	9.8	6.9	6.1	10.1	12.6	14.6	9.5
HLW	1,500	11.1	11.1	11.1	11.1	13.4	11.1	11.1
Total		20.9	18.0	17.2	21.2	26.0	25.7	20.6
TRUW	70,000	460	320	280	470	590	680	440
HLW	70,000	520	520	520	520	620	520	520
Total		980	840	800	990	1,210	1,200	960

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

8.1.3 Summary of TRUW Treatment Facility Costs

The life-cycle capital charges and operating costs (excluding decommissioning costs) for two 1,500 MTU/yr reprocessing facilities processing a total of 70,000 MTU are shown for each treatment option in Table 8.3.

TABLE 8.3. Summary of TRUW Facility Amortized Capital and Operating Costs for the Six TRUW Treatment Options[a]

Waste Type	MTU Basis	Cost by Option, $M						
		1	2	3	4	5A	5B	6
TRUW	1,500	26.3	31.3	32.9	47.2	55.0	64.5	47.0
HLW	1,500	53.5	53.5	53.5	53.5	63.3	53.5	53.5
Total		79.8	84.8	86.4	100.7	118.3	118.0	100.5
TRUW	70,000	1,230	1,460	1,540	2,200	2,570	3,010	2,190
HLW	70,000	2,500	2,500	2,500	2,500	2,950	2,500	2,500
Total		3,730	3,960	4,040	4,700	5,520	5,510	4,690

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

8.2 TRANSPORTATION COSTS

The processed TRUW and HLW are assumed to be shipped by railcar to a commercial repository 2,000 miles from the waste processing facility. Similarly, the LLW resulting from decontamination or dilution is to be transported by truck to a commercial LLW disposal site in the eastern U.S., 300 miles from the waste processing facility. Transportation is to be provided by private industry.

The transportation cost for TRUW and HLW consists of a cask-leasing fee and general freight charges (including security if required). Except for the shipment of the waste in 160-gal containers (see footnote (c) on Table 0.5), the cask leasing fee is taken directly from the McKee study. The freight charges were derived from information provided by McNair et al. (1984). The cost of transporting the LLW is based on information in DOE/LLW-6Td (EG&G Idaho, Inc. 1983).

The transportation costs for TRUW, LLW, and HLW are given in Table 8.4, based on 1,500 MTU/yr reprocessed and on 70,000 MTU total fuel reprocessed from two reprocessing plants. See Appendix O for details of the transportation costs.

TABLE 8.4. Transportation Costs for the Six TRUW Treatment Options[a]

Waste Type	MTU Basis	Cost by Option, $M						
		1	2	3	4	5A	5B	6
TRUW	1,500	30.1	6.8	26.3	2.6	0.2	0.4	2.45
LLW	1,500	0	0	0	0	0.9	0.9	0.04
HLW	1,500	6.7	6.7	6.7	6.7	11.5	6.7	6.7
Total		36.8	13.5	33.0	9.3	12.6	8.0	9.2
TRUW	70,000	1,400	320	1,230	120	10	20	110
LLW	70,000	0	0	0	0	40	40	2
HLW	70,000	310	310	310	310	540	310	310
Total		1,710	630	1,540	430	590	370	420

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

8.3 DISPOSAL COSTS

The disposal costs for TRUW and HLW were estimated using the RECON repository cost model (Clark et al. 1983), which calculates the life-cycle construction, operating, and decommissioning costs of geologic repositories. The repository used is based on the 1983 reference design concept for BWIP (Kaiser Engineers Inc./Parsons, Brinkerhoff, Quade, and Douglas, Inc. 1983). The repository is assumed to have the capacity to accept the 70,000 MTU of reprocessed waste used as the basis in this study. It was also assumed that the RH TRUW and HLW would be remotely placed into horizontal boreholes in the walls of the underground tunnels, and that the CH TRUW would be co-emplaced with the HLW with long-lived overpacks. The computer model includes all costs for repository design, surface and subsurface construction and excavation, backfilling, sealing, and decommissioning; and operating costs for waste receipt, package transport, and emplacement. Because the repository disposal costs are related to the relative amounts of the different types of wastes received, the repository costs were calculated based on the amounts of each waste type and the canister sizes for each treatment option in this study (see Table 7.9).

The life-cycle disposal costs generated by RECON are given in Table 8.5, as well as the LLW disposal costs for LLW generated in Options 5 and 6. It should be noted that as the TRUW volumes decrease, the TRUW disposal costs also decrease. However, the HLW costs increase, since facility costs are shifted to HLW. Thus it is important to consider total HLW and TRUW costs when estimating TRUW disposal costs.

The LLW costs are based on the Barnwell LLW disposal facility rate schedule (see Appendix E). Additional details of the disposal cost calculations are given in Appendix D.

TABLE 8.5. Disposal Costs for the Six TRUW Treatment Options[a]

Waste Type	MTU Basis	Cost by Option, $M						
		1	2	3	4	5A	5B	6
TRUW	1,500	47.6	31.1	39.6	12.6	4.1	4.1	13.5
LLW	1,500	0	0	0	0	11.6	11.6	0.07
HLW	1,500	56.6	59.8	59.6	64.5	68.8	67.7	63.7
Total		104	91	99	77	85	83	77
TRUW	70,000	2,230	1,450	1,850	590	190	190	630
LLW	70,000	0	0	0	0	540	540	3
HLW	70,000	2,640	2,790	2,770	3,010	3,210	3,160	2,970
Total		4,870	4,240	4,620	3,600	3,940	3,890	3,600

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

8.4 TOTAL LIFE-CYCLE COSTS

The total life-cycle costs (exclusive of decomissioning and any R&D costs) for management of TRUW, HLW, and LLW from the six TRUW treatment options are given in Table 8.6. These values are taken from Tables 8.3, 8.4 and 8.5.

TABLE 8.6. Total Life-Cycle Cost for Management of TRUW, HLW, and LLW[a]

Cost Category		Life-Cycle Costs by Option, $M/70,000 MTU[b]						
		1	2	3	4	5A	5B	6
Treatment facility	TRUW	1,230	1,460	1,540	2,200	2,570	3,010	2,190
	HLW	2,500	2,500	2,500	2,500	2,950	2,500	2,500
	Subtotal	3,730	3,960	4,040	4,700	5,520	5,510	4,690
Transportation	TRUW	1,400	320	1,230	120	10	20	110
	LLW	0	0	0	0	40	40	2
	HLW	310	310	310	310	540	310	310
	Subtotal	1,710	630	1,540	430	590	370	420
Disposal	TRUW	2,230	1,450	1,850	590	190	190	630
	LLW	0	0	0	0	540	540	3
	HLW	2,640	2,790	2,770	3,010	3,210	3,160	2,970
	Subtotal	4,870	4,240	4,620	3,600	3,940	3,890	3,600
Total cost	TRUW	4,860	3,230	4,620	2,910	2,770	3,220	2,830
	LLW	0	0	0	0	580	580	5
	HLW	5,450	5,600	5,580	5,820	6,700	5,970	5,780
Grand total cost		10,310	8,830	10,200	8,730	10,050	9,770	8,620

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) Life-cycle cost = (cost based on 1,500 MTU) x (70,000 MTU/1,500 MTU).

8.5 REFERENCES

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

EG&G Idaho, Inc. 1983. Directions in Low-Level Radioactive Waste Management, An Analysis of Low-Level Waste Disposal Facility and Transportation Cost. DOE/LLW-6Td, Idaho Falls, Idaho.

Kaiser Engineers Inc./Parsons, Brinkerhoff, Quade, and Douglas, Inc. 1983. Conceptual System Design Description, Nuclear Waste Repositories in Basalt, Project B-301. BWI-SD-006, Rockwell Hanford Operations, Richland, Washington.

McKee, R. W., L. L. Clark, P. M. Daling, J. F. Nesbitt and J. L. Swanson. 1984. "Economic Analysis of Waste Management System Alternatives for Reprocessing Wastes." Waste Management 1984, University of Arizona, Tucson.

McNair, G. W. et al. 1984. Truck and Rail Charges for Shipping Spent Fuel and Nuclear Waste. PNL-4064, Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy. 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028 in 5 volumes, U.S. DOE, Washington, D.C.

9.0 COMPARISON OF TREATMENT STRATEGIES

The primary emphasis of this study is the selection and evaluation of potential treatment methods for TRUW. Waste management system cost analyses of the selected options were provided in Section 8. The factors of waste acceptance at the repository and the process and operational characteristics are discussed and compared in this section. Following the discussions of these two factors, a summary and comparison of the various treatment options are presented.

9.1 WASTE FORM CHARACTERISTICS

The general requirements for the waste forms were reviewed in Section 4 in conjunction with the regulatory requirements for waste disposal. It was recognized that the final disposal method for TRUW has not been established, although geologic disposal is assumed in this study. Also, the absolute acceptability of a waste for disposal cannot be stated with certainty, since detailed waste form requirements have yet to be established. Obviously, the better the properties of the waste form, the greater the likelihood of its being considered acceptable for disposal.

From the analysis in Section 4, it can be noted that the waste form may be required to have specific characteristics, particularly for deep geologic disposal. The characteristics from Table 4.1, which can be controlled by waste form selection, are compared in Table 9.1. Several factors presented in Table 4.1 are similar and are thus considered together in Table 9.1. For example, solubility, leach rate, and release rate (from the near field at the repository) are all measures of chemical durability that are included in Table 9.1 under "Release Rate." The following are considerations for the qualitative evaluations in Table 9.1.

- Combustible materials are present in as-generated wastes and are less combustible (and will not propagate a flame front) when mixed with cement. Incineration removes all combustible and biodegradable material from the waste.

TABLE 9.1. Comparison of Likely Waste Form Characteristics for the Six TRUW Treatment Options, with Potential Requirements

Treatment Option	Combustible Material Present	Particulates Present	Pyrophoric Free Liquid Present	Gas Material Present
1. No treatment	Yes	Yes	No	Possible (hulls)
2. Minimum treatment	Yes	Yes	No	Likely (hull fines)
3. Minimum number processes	Yes, but cemented	No	Not likely	Diluted
4. Maximum volume reduction without decontamination	Slight	No	No	No
5. Maximum volume reduction with decontamination	Slight	Slight	No	Treated
6. Noncombustible waste forms	None	No	No	No

Generation Likely	Subject to Biodegradation	Structural Stability	Void Spaces Present	Release Rate	Radiation Resistance
Possible	Possible	None	Yes	Some forms have high potential release	Probably poor
Possible	Possible	Poor	Yes	Some forms have high potential release	Probably poor
Possible	Reduced potential	Good	No	High pH will reduce actinide release rates	Probably fair
No	No	Good	No	Low	Generally good
No	No	Most forms	Some	Low	Good
No	No	Good	No	Low	Good

- Particulates will be present in several wastes, such as fluorinator fines and cladding hulls, unless immobilized. Particulates have high surface areas that tend to increase the release potential.
- No liquids are anticipated as a direct waste stream. A poorly prepared cement mixture, however, may have excess water after curing (the free liquid could be used for subsequent cementing batches). Quality control checks should detect and prevent free liquid from being shipped.
- Cladding hull fines can be pyrophoric under certain conditions, and crushing of the hulls may generate additional fines. Diluting the hulls with cement should reduce the pyrophoric tendency, and forming metal billets should eliminate any pyrophoric potential.
- Gas generation may be detrimental in contributing to release during storage and disposal. Radiolysis of organics and water in cement is a potential source of gas generation.
- Low bulk density materials do not have structural stability without a supporting canister. Structural stability for about the first 100 years (during the emplacement and potential retrievability period at the repository) may be important to prevent breaching of the overburden above a repository. However, over the long term at the depth of a deep geologic repository, the potential for breaching the overburden resulting from collapse of the waste is negligible, and subsidence of the overburden is probably not a major concern.
- Structural stability is generally improved with lower void space. However, as stated above, the importance of structural stability over the long term may or may not be important.
- The release rates from most of these waste forms have not been measured, even in comparison with HLW forms. Therefore, it is difficult to judge whether the materials could meet the stringent 10 CFR 60 (U.S. NRC 1983) release rate requirement of less than 1 part in 100,000 per year, although some comparison of TRUW forms has been made (Ross et al. 1981).

- Radiation resistance is a consideration for maintenance of structural stability and for possible gas generation from radiolysis. Some of the forms have not been well characterized for these properties, and future development will need to emphasize waste form testing along with process development (Roberts 1981). The expected waste form performance given in Table 9.1 takes these considerations into account.

As might be anticipated, waste forms from Option 1 (no treatment) and Option 2 (minimum treatment) have the greatest potential for being unacceptable for deep geologic repository disposal. The major concerns are with 1) hull fines, which may be reactive and pyrophoric; 2) combustible materials, which are subject to biodegradation, gas generation, and fire; 3) particulate material, which has the potential for higher releases of radioactivity, particularly during accidents with canister failure; and 4) high potential radionuclide release rates. High-integrity canisters may provide an intermediate-term solution for all of these concerns.

Option 3 (minimum number of processes and products) involves cementing all of the wastes and thus reduces the potential waste form concerns identified above, but it does not completely eliminate them. Additional testing and characterization would appear to be necessary should this option be selected.

Option 4 (maximum volume reduction without decontamination) produces generally good waste form properties. The remaining concerns result from the residual quantities of organic materials from the treatment of SAC wastes. Possible alternative treatments of SAC wastes are noted in other options.

Option 5 (maximum volume reduction with decontamination) presents concerns from the recognition that decontamination of all the material may not be possible, which could leave some material unchanged from its as-generated condition.

Option 6 (noncombustible waste forms) results in waste forms with the most favorable characteristics. This is primarily because of the limitations noted for treating GPT and SAC wastes noted for Options 4 and 5.

9.2 PROCESSING CHARACTERISTICS

The processing characteristics for each treatment option have been evaluated qualitatively. Characteristics have been evaluated in the four subcategories of 1) process and operational safety, 2) complexity of the treatment system, 3) status of technology, and 4) flexibility of the processes. These evaluations are given in the following subsections.

9.2.1 Process and Operational Safety

The safety of the treatment methods concerns the risk to operational staff and the public from the process operations, and includes consideration of inherent accident potential with respect to chemicals, fire or explosions, mechanical operations, electrical accidents, and radiochemical releases. All of the processes would be safe when implemented, but some inherent safety concerns require that additional safety provisions be incorporated into the design and operational procedures. Detailed risk analyses, which are beyond the scope of this study, would be required to quantify the relative safety of the different processes.

Chemical hazards are determined based on the use of hazardous materials and the recognition that handling such materials (e.g., acids, bases, or toxic materials) can present accident potential to personnel. However, the processes selected for this study generally do not require the use of these agents; thus all options have low chemical hazards. In Option 5, cryogenic cracking of the cladding hulls would require the use of liquid nitrogen, which requires some care to avoid freezing or gas pressurization.

Fire or explosion hazards are related to the generation of hull fines, the handling of organic and combustible materials, and the use of high temperature operations.

Mechanical hazards are a concern where operating personnel are in the proximity of mechanical equipment and where high pressures are used.

Electrical hazards are approximately a function of the amount of electrically powered equipment used. Electrical power is likely to he handled safely, and thus none of the options would likely pose a major hazard to operating personnel.

Radiochemical release is related to the need to handle radioactive materials and to treat off gases from the processes, particularly the processes at high temperatures, which have a higher potential for volatilization of radionuclides. For example, metal melting may pose a volatilization concern because tritium in the cladding hulls will be partially or totally volatilized during melting and will need to be captured in the off-gas system.

The qualitative evaluation of the process and operational safety is summarized in Column 2 of Table 9.2. A review of Table 9.2 shows that the simpler the treatment system, the lower the potential hazard. Options 1, 2, and 3 appear to have the most inherent process and operational safety. (However, it should be noted again that the evaluations in Table 9.2 are relative, and all of the processes would pose a low risk as implemented.) Additional details on development of the evaluation are given in Appendix F.

9.2.2 Complexity of the Treatment System

The complexity of the treatment system can be qualitatively estimated by the number of treatment processes and the number of steps in each process. (In addition, the more complex the treatment, the greater the cost of process equipment, facility space and operations, as identified in Section 8).

The results of the qualitative evaluation of treatment system complexity are summarized in Column 3 of Table 9.2. The table shows that the more complete treatment options (i.e., Options 4, 5, and 6) involve more complex treatment systems. Additional details of the evaluation of system complexity are given in Appendix F.

9.2.3 Status of Technology

The status of technology is important in selecting treatment strategies. The time required for implementation of the technology, the cost of R&D, and the availability and experience in design and operation of treatment systems are all related to the status of technology. These factors were estimated qualititatively in this study, and the overall status of technology was identified by classification of the development stage of the major process steps. It should be recognized that most of these technologies have been developed for other types of radioactive waste, particularly defense TRUW and LLW.

TABLE 9.2. Overall Qualitative Comparison of Processing Characteristics for the Six TRUW Treatment Options[a]

Treatment Option	Process and Operational Safety	Process Simplicity	Status of Technology	Process Flexibility	Overall[b]
1. No treatment	Very good	Very good	Very good	Very good	Very good
2. Minimum treatment	Good	Good	Very good	Good	Good +
3. Minimum number of processes and products	Good	Good	Very good	Good	Good +
4. Maximum volume reduction without decontamination	Fair	Moderate	Moderate	Fair	Fair +
5. Maximum volume reduction with decontamination	Moderate	Fair	Fair	Fair	Fair
6. Noncombustible waste forms	Moderate	Moderate	Good	Good	Good

(a) The relative ratings are from very good (the most favorable) to fair (the least favorable in the group). No attempt was made to weight the four categories.
(b) A "+" indicates that the relative rating falls between that indicated and the next highest rating.

Development of technology can be expected to continue for both defense TRUW and commercial LLW, reducing the amount of technology development necessary for commercial TRUW. Timing does not currently appear to be a major concern because of the delay in the implementation of reprocessing in the commercial nuclear fuel cycle. The cost for R&D, while significant, can be expected to be small (in the range of a few tens of millions of dollars) compared to the potential savings from implementation of the technology (up to 1.7 billion dollars). R&D costs for commercial wastes may be reduced by delaying development of the technology, since similar technology is being developed for defense wastes, but costs could be increased if the delay results in a shortened development schedule that requires parallel development efforts. Total development (defense plus commercial) costs may not be much different regardless of the schedule.

The overall status of technology was identified by classification of the stage of development of the major process steps. Timing does not appear to be a major concern because a major TRUW treatment system will not be needed until

some time in the future. The cost of R&D for treatment systems can be significant and should not exceed the value of savings resulting from the treatment optimization. Availability of maintenance service and experience can provide economic benefits.

The results of the qualitative evaluation of the technology status of the treatment options are summarized in Column 4 of Table 9.2. As might be expected, the status of technology for the simpler treatment options (Options 1, 2, and 3) is the most favorable. Additional details of the evaluation of the status of technology are given in Appendix F.

9.2.4 Flexibility of Processes

In some of the treatment options, the individual treatment processes are expected to treat wastes with a wide variety of characteristics. Some questions remain regarding the ability of all of the processes to perform as desired. The qualitative evaluation of the flexibility of the treatment processes to accommodate the anticipated variations in waste streams is summarized in Column 5 of Table 9.2.

The processes all appear to be appropriate, with some having minor potential difficulties. This is largely because the process selection during the early part of the study eliminated processes with serious questions. Additional details of the evaluation of process flexibility are given in Appendix F.

9.2.5 Overall Evaluation of Processing Characteristics

The overall qualitative evaluation of the processing characteristics is given in the last column of Table 9.2. This evaluation is a composite of the four factors given in the prior four columns. No attempt was made to weight the four factors; thus they were all assumed to be of approximately equal weight.

Table 9.2 shows that the simpler treatment options (Options 1, 2, and 3) possess the more favorable processing characteristics. However, Option 6 follows closely behind the first three, while Options 4 and 5 are significantly less favorable.

9.3 OVERALL COMPARISON OF TREATMENT OPTIONS

In this subsection the six options are compared on an overall basis using the quantitative economic considerations of the waste management system from Section 8 (Table 8.6) and the qualitative waste form and processing characteristics given in Subsections 9.1 (Table 9.1) and 9.2 (Table 9.2). From this information, the options are ranked 1 (most favorable) through 6 (least favorable) in each of the three major comparison categories. This ranking is shown in Columns 2, 3, and 4 of Table 9.3. This technique was used to force discrimination among the various categories, even though the differences were small in some cases.

An approximate overall ranking of the options is given in Column 5 of Table 9.3. This ranking, obtained by simple addition of the numbers in the prior three columns, inherently assumes equal weighting of the categories in the first three columns. However, this simple ranking system provide some valuable insights, indicating that Option 6 appears to be the most favorable and Options 1 and 5 appear to be the least favorable. The more extensive treatment options (Options 4, 5, and 6) are ranked the highest in the waste form category, with the ranking for Option 6 as the most favorable. Option 6 also presents the most favorable system economics and has the most favorable

TABLE 9.3. Summary Ranking of the Six TRUW Treatment Options[a]

Option	System Economics	Waste Form Characteristics	Processing Characteristics	Approximate Overall Ranking[b]
1	6	6	1	13
2	3	5	2	10
3	5	4	3	12
4	2	2	5	9
5	4	3	6	13
6	1	1	4	6

(a) Ranking is from 1 (most favorable) to 6 (least favorable of the group).
(b) Approximate overall ranking is by addition of the prior three values for each option, with the lower values being the most favorable.

processing characteristics of the more extensive treatment options (Options 4, 5, and 6). Option 5 appears to be the least favorable of the more extensive treatment options.

Although waste form requirements may not be known currently, they may well provide "go/no-go" bases for evaluating the waste forms for the various strategies. If so, the options with the lower waste form ranking could well be eliminated, and the better waste forms would have a greater chance of meeting the requirements.

Based on these evaluations, it appears that Option 6 may have the most favorable characteristics of all the options studied. Option 4 appears to have the next most favorable characteristics of the more extensive treatment options, and ranks least favorable only in the processing characteristics (which could likely be improved with development).

The strength of selecting Option 6 can be illustrated by noting that even with a doubling of the relative cost of processing (the characteristic with the lowest ranking for Option 6), it would still be favored over the other options. Since it has the highest ratings for both economics and waste form characteristics, Option 6 would be preferred as long as the combined weighting for economics and waste form is as low as 40% of the total, based on this analysis method.

Options 1, 2, and 3 would require little or no R&D, and their relative ranking would likely be unaffected by further technology development. Technology for treating contact-handled TRUW for Option 6 is being developed for several different types of defense waste. Development of shredding, incineration, and cementing technology for commercial wastes can be limited to remotizing the processes and equipment modifications for the specific waste types. No totally new technology is needed.[a]

(a) The major processes for Option 6 have some history in radioactive waste treatment. Melting of metals was originally considered for treating cladding hulls in the early 1970s, and melting technology is well established commercially for a wide variety of metals. Evaluation of alternative melting processes has recently been completed (Montgomery and Nesbitt 1983), and initial tests have been completed that show much promise for vacuum induction melting (Montgomery et al. 1984). Shredding, incineration, and cementing technology was selected by INEL (Clements et al. 1984) and other sites with defense TRUW for treatment of TRUW.

9.4 REFERENCES

Clements, T. L., et al. 1984. Processing and Certification of Defense Transuranic Wastes at the INEL. EGG-M-26083, EG&G Co., Idaho Falls, Idaho.

EGG, Co. 1982. Conceptual Design Report for TAN 607 Process Experimental Pilot Plant (PREPP). EG&G Co., Idaho Falls, Idaho.

Montgomery, D. R. 1984. Consolidation of Simulated Nuclear Metallic Waste by Vacuum Coreless Induction Melting. PNL-5254, Pacific Northwest Laboratory, Richland, Washington.

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

Roberts, F. P. 1981. An Assessment of Radiation Effects in Defense Transuranic Waste Forms. PNL-3913, Pacific Northwest Laboratory, Richland, Washington.

Ross, W. A., et al. 1981. "A Comparative Assessment of TRU Waste Forms and Immobilization Processes." In Scientific Basis for Nuclear Waste Management. Elsevier Science Publishing Co. New York.

U.S. Nuclear Regulatory Commission. 1984. Code of Federal Regulations, Title 10, Energy; Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories Technical Criteria. Final Rule, U.S. Federal Register, Vol. 48, No. 120, June 21, 1983, pp. 28194-28229. U.S. NRC, Washington, D.C.

10.0 CONCLUSIONS AND RECOMMENDATIONS

This study evaluates six options for the treatment of TRUW from a reference reprocessing plant. These options represent specific treatment strategies involving no treatment, minimum processing, minimum number of processes and products, maximum volume reduction, decontamination to remove material from the TRUW category, and the preparation of waste forms without combustibles. Treatment processes were selected to correspond to each of these objectives, and the anticipated volumes of treated waste from a Barnwell-type plant were calculated. These volumes were used with the RECON computer code (Clark et al. 1983) and Chem-Nuclear LLW disposal costs (see Appendix E) to calculate disposal costs for the various options. Transportation and treatment costs were also estimated and summed with disposal costs to compare the costs of the six options. Decommissioning and R&D costs have not been included in the economic analysis, but they will be much lower than the overall system costs that have been included. The options were also compared based on waste form and process considerations. Based on this study, the following conclusions and recommendations are warranted:

- Option 6, noncombustible waste forms, is the preferred option from both economic and waste form standpoints, and Option 4, maximum volume reduction without decontamination, is the next preferred alternative. The economic incentive to treat the waste is a savings of about $1.6 billion, based on the waste from reprocessing 70,000 MTU of spent fuel and on comparison with the no treatment option. Options 4 and 6 treat the metallic waste by melting and the combustible wastes by incineration. The processes in Option 6 result in only two waste forms: metal ingots and cement that incorporate the wastes. Development of the technology for this option, including metal melting, incineration, shredding, and cementing, should be given first priority.
- When compared with the no treatment option, all of the treatment options in this study offer economic and waste form incentives, and

thus indicate the importance of treating TRUW. This conclusion was also reached by McKee et al. (1984) in their study of commercial TRUW.

- Fuel cladding hulls and hardware comprise the most important TRUW streams from reprocessing because of their large volume, high radioactivity, and the costs for their management. The processes with the greatest economic benefits are those with technology that produces large volume reductions of the fuel cladding hulls and hardware. Decontamination applied to hulls alone may be an effective treatment for this waste stream, but this will require verification. Some of the radioactivity (i.e., activation products) in cladding hulls are not removable by decontamination. Decontamination of other streams does not appear to be justified because of the added treatment costs and process complexity. A major consideration in decontamination of TRUW stems from the recognition that all of the wastes cannot be decontaminated, and thus other treatment methods must also be implemented, which increases processing complexity and treatment costs.
- There appear to be several incentives for incinerating combustible wastes, including volume reduction and the elimination of combustible materials from wastes sent to disposal. A direct comparison of incineration with alternative treatments was not possible from the final results and should be studied further.
- In evaluating the decontamination of fuel hardware, it was recognized that the high level of radiation from ^{60}Co in these materials may require their disposal in a repository, both from an economic viewpoint and because of the difficulty that LLW sites have in handling the activity associated with this material.
- Volume reduction is a very important consideration from the perspective of overall system economics.
- Simple compaction of the wastes is economically attractive, but waste form characteristics remain a concern for disposal.

- Combining small volumes of TRUW with HLW may be economic if it does not significantly increase HLW volume. However, treating the sludge resulting from hull decontamination by this method is very costly because it increases the size of the HLW vitrification system required.
- HEPA filters are a major waste stream that can be significantly reduced in volume. HEPA filters, in addition to other materials, contain organic glues and aluminum spacers that complicate their treatment. The available data regarding treatment of filters are incomplete and should be developed further. Treatment of filters should be given high priority in R&D planning with respect to specific waste types.
- One of the other problem waste materials is PVC; its high chloride content makes it unfavorable for incineration and limits the combining of the residues from incineration with HLW glass. Thus there is an incentive to replace PVC with alternative materials that may simplify waste treatment and reduce its costs.
- Reduced waste generation, one method of volume reduction not considered in this report, should be evaluated, particularly in its potential impact on the design and operation of treatment facilities. With new practices it may be possible to reduce the volume of the wastes that need treatment for a much lower cost than the cost of treating the resulting wastes from current practices.
- Development and characterization of TRUW forms are needed to allow assessment of their potential behavior in disposal environments and their conformance with NRC and EPA requirements.
- This strategy analysis should be reviewed periodically as new technology is developed, as new practices are applied in fuel reprocessing, and as new applications for waste treatment are identified.

10.1 REFERENCE

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

McKee, R. W., L. L. Clark, P. M. Daling, J. F. Nesbitt, and J. L. Swanson. 1984. "Economic Analysis of Waste Management System Alternatives for Reprocessing Wastes." Waste Management 1984, pp. 383-393. University of Arizona, Tucson.

APPENDIX A

TRUW CHARACTERISTICS BY WASTE TYPE

TABLE A.1. TRUW Characteristics by Waste Type (Darr 1983)

Waste Type	Stream	Containers/ 1,500 MTU	Container Size, gal	Quantity of Contained Waste/1,500 MTU		TRU Content, nCi/g	Container Dose Rate, mR/hr
				ft^3	kg		
Hulls and hardware	21	300	600	2.25E4	4.86E5	2.2E4	4.6E6
Filters (metal framed)	25B	51	80	1.80E2	6.63E2	3.70E2	1.30E2
		18	80	6.15E1	2.34E2	1.20E3	4.0E2
		4	80	9.5E0	5.2E1	3.0E2	2.30E3
	25C	3	600	3.8E1	1.35E2	2.0E5	8.0E4
		21	600	2.62E2	9.45E2	2.0E6	8.0E5
	45	33	80	6.6E1	4.29E2	3.70E2	1.30E2
		11	80	2.2E1	1.43E2	1.20E3	4.10E2
	52A	52	80	1.89E2	6.76E2	5.00E3	3.0E-1
		497	80	1.81E3	6.46E3	8.0E4	4.5E0
		251	80	9.14E2	3.26E3	6.0E5	3.1E1
	52B	1	55	3.0E0	3.8E1	4.00E3	3.0E-1
		19	55	5.7E1	7.22E2	6.0E4	3.5E0
		30	55	9.0E1	1.14E3	3.0E5	1.7E0
	63A	2	600	3.0E1	9.0E1	8.0E4	8.0E4
		18	600	2.70E2	8.10E2	8.0E5	8.0E5
	63B	77	80	3.08E2	1.00E3	1.20E2	1.30E2
		27	80	1.08E2	3.51E2	3.80E2	4.10E2
		9	80	3.6E1	1.17E2	2.00E3	2.00E3

TABLE A.1. (contd)

Waste Type	Stream	Containers/ 1,5D0 MTU	Container Size, gal	Quantity of Contained Waste/1,500 MTU		TRU Content, nCi/g	Container Dose Rate, mR/hr
				ft^3	kg		
Filters (wood framed)	25B	153	80	5.38E2	1.99E3	3.70E2	1.30E2
		52	80	1.84E2	6.76E2	1.20E3	4.00E2
		12	8D	2.85E1	1.56E2	3.00E2	2.30E3
GPT (combustible)	27	128	55	9.60E2	2.69E3	2.20E2	1.50E2
		48	55	3.60E2	1.01E3	6.80E2	4.80E2
		42.4	55	3.18E2	8.90E2	4.50E3	3.20E3
	53	94.5	55	6.21E2	1.98E3	4.30E3	7.0E-1
		137.6	55	9.05E2	2.89E3	6.0E4	1.0E1
		72	55	4.74E2	1.51E3	4.0E5	6.0E1
	65	36	55	2.40E2	7.56E2	2.20E2	4.80E2
		32	55	2.14E2	6.72E2	1.50E3	3.20E3
GPT (noncombustible)	27	32	55	2.40E2	6.72E2	2.20E2	1.50E2
		12	55	9.0E1	2.52E2	6.80E2	4.80E2
		10.6	55	8.0E1	2.23E2	4.50E3	3.20E3
	53	23.6	55	1.55E2	4.96E2	4.30E3	7.0E-1
		34.4	55	2.26E2	7.22E2	6.0E4	1.0E1
		18	55	1.18E2	3.78E2	4.0E5	6.0E1
	65	9	55	6.0E1	1.89E2	2.20E2	4.80E2
		8	55	5.3E1	1.68E2	1.50E3	3.20E3

TABLE A.1. (contd)

Waste Type	Stream	Containers/ 1,500 MTU	Container Size, gal	Quantity of Contained Waste/1,500 MTU		TRU Content, nCi/g	Container Dose Rate, mR/hr
				ft^3	kg		
SAC Waste	23	21	600	4.26E2	1.66E3	4.50E2	2.60E2
		7	600	1.42E2	5.53E2	8.90E2	5.30E2
		2	600	4.1E1	1.58E2	1.3E4	8.00E3
		2	600	4.1E1	1.58E2	1.3E5	8.0E4
	67	4	600	2.92E2	3.16E2	4.4E3	8.00E3
		1	600	7.3E1	7.9E1	4.4E4	8.0E4
Failed equipment	24	1	600	5.0E1	9.00E2	1.60E2	5.20E2
		1	600	5.0E1	9.00E2	2.40E3	7.80E3
		1	600	5.0E1	9.00E2	2.4E4	8.0E4
	51A	2	55	1.4E1	4.00E2	6.80E2	1.0E-1
		30	55	2.14E2	6.00E3	6.80E3	1.2E0
		38	55	2.71E2	7.60E3	1.2E5	2.0E1
	51B	1	600	5.0E1	9.00E2	2.0E3	4.0E-1
		3	600	1.50E2	2.70E3	1.2E4	1.7E0
	62	1	600	7.0E1	9.00E2	7.70E2	7.80E3
Fluorinator solids	41	93	55	6.18E2	3.10E4	2.59E2	8.70E2

A.1 REFERENCE

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

APPENDIX B

DETAILS OF THE ESTIMATION OF FINAL PROCESSED TRUW QUANTITIES

APPENDIX B

DETAILS OF THE ESTIMATION OF FINAL PROCESSED TRUW QUANTITIES

In Section 7, the TRUW treatment options are described and the final quantities of processed TRUW resulting from each option are presented. The assumptions leading to these quantities are described in more detail in this appendix.

B.1 GENERAL ASSUMPTIONS

Some of the general assumptions are listed below.

1. The internal container volumes and tare weights are provided in Table B.1.

TABLE B.1. Internal Container Volumes and Tare Weights

Nominal Container Size	Approx. Internal Dimensions dia x ht, in.	Internal Volume, m^3	Tare Weight, kg
55 gal	22.5 x 34.0 x 0.05	0.208	31
80 gal	27.3 x 30.5 x 0.05	0.303	31
160 gal	22.9 x 90.0 x 0.375	0.606	430
600 gal	44.0 x 90.0 x 0.375	2.271	1,000
53 gal HLW	12.3 x 119.5 x 0.25	0.231	160

2. The containers are loaded to 90 vol% (in the case where the wastes are treated and repackaged).
3. The volume reduction factors are defined as initial volume divided by final volume.

B.2 OPTION 1 - NO TREATMENT

The weights, volumes, and number of containers of untreated and unpackaged TRUW are summarized in Section 5.

B.3 OPTION 2 - MINIMUM TREATMENT

In this TRUW treatment option, most of the wastes are compacted to reduce their volume. An in-can compaction process is assumed, with a container size of 160 gal.

The hulls and hardware are RH compacted in RH batches. A compaction factor of 3.33 is assumed (McKee et al. 1984).

Although Allied-General Nuclear Services (1978) specifies that failed equipment is not compactible, it is assumed in this study that some compaction can be obtained with high pressure compaction. The failed equipment is compacted in RH or CH batches. Size reduction is performed as required prior to compaction. A volume reduction factor of 1.67 (half that for hulls and hardware) is assumed for the failed equipment.

The filters are size reduced and compacted in RH or CH batches. A volume reduction factor of 4.0 is assumed for the filters.

Eighty wt% of the GPT and 60 wt% of the SAC waste are combustible and are assumed to be compacted at a volume reduction factor of 4.0. A volume reduction factor of 1.67 is assumed for the noncombustible portions of these wastes. These wastes are also compacted in CH and RH batches.

The fluorinator solids are left in their initial containers and are not treated.

The assumptions used to estimate the surface dose rate of the packaged waste are:

- Compaction provides negligible additional shielding.
- Surface dose is a weak function of geometry.
- Surface dose rate can be approximated by multiplying the initial surface dose rate by the ratio of initial packaged volume to the final packaged volume.

B.4 OPTION 3 - MINIMUM NUMBER OF PROCESSES AND PROOUCTS

For this treatment option, all TRUW is immobilized in cement. The hulls and hardware are mixed with cement and placed back into 600-gal containers. It is assumed that the cement increases the untreated, unpackaged volume by 10 vol%.

Premixed cement grout is poured over the failed equipment in a carbon steel container of the same size as the original stainless steel container. Because the failed equipment has substantial void space to accommodate an adequate amount of cement, it is assumed that there is no increase in volume. The cement is also assumed to reduce the surface dose by a factor of 4.

The filters and GPT-SAC waste are shredded, combined with the fluorinator solids, and mixed with cement and water in CH or RH batches in an in-drum mixer. The following cement recipe is used (Schneider and Ledebrink 1983):

- 200 kg cement
- 80 kg water
- 20 kg salt ($NaNO_3$)
- 40 kg soft waste (cellulose, filter media, wood filter frames)
- 60 kg hard waste (metal, fluorinator solids), for a total weight of 400 kg and a density of 2000 kg/m^3.

The cementing is assumed to reduce the surface dose of these wastes by a factor of 2. This factor is lower than that assumed for the cemented failed equipment because the shredded filters, GPT-SAC waste, and fluorinator solids have a smaller void volume.

B.5 OPTION 4 - MAXIMUM VOLUME REOUCTION WITHOUT DECONTAMINATION

In this option, the metals and ceramics are melted, the cellulose materials are incinerated, and the plastic and rubber are hot pressed. The processed waste is loaded at 90 vol% in 160-gal containers. The densities of the melted TRUW are:

Waste Type	Density, kg/m^3	90% Density, kg/m^3
Hulls and hardware	6,500	5,850
Failed equipment, metal filter frames, metallic GPT-SAC waste	7,800	7,080
Melted ash, scrub residue and filter media mixture	2,300	2,070
Plastic and rubber	1,200	1,080

The hulls and hardware are melted to 90% of theoretical density. The weight of hardware is taken to be 17.4% of the total hulls and hardware weight (U.S. DOE 1979).

As in Option 2, the CH streams that could potentially become RH after treatment need to be identified. The criteria in Option 2 are used again here:

$$D_o(V_o/V_f) > 200 \text{ mR/hr} \rightarrow \text{RH waste}$$

where

D_o = surface dose of original drum (mR/hr)

V_o = volume of untreated and unpackaged waste based on drum volume (m^3)

V_f = volume of treated and packaged waste based on drum volume (m^3).

The failed equipment is separated into CH and RH batches. Some size reduction may be required prior to melting. The failed equipment is melted to 90% theoretical density in CH or RH batches.

The filters are 33.3 wt% frame, 33.3 wt% media, and 33.3 wt% adhesive and organics. It is assumed that the CH/RH category of the metal frames does not change due to processing. The filters are shredded and burned in an incinerator, resulting in ash, media, and metals. The metals are removed and melted with the failed equipment to 90% of theoretical density in CH or RH metal

batches. The ash, filter media, and scrubber solution residues are concentrated to 90% of theoretical density by incorporation into the metal melts. These melted residues are assumed to be RH.

The contamination is assumed to be equally distributed for the GPT-SAC waste. The GPT-SAC waste is sorted by material type and the metals are melted in CH or RH batches. The rubber and plastics are hot pressed to 90% theoretical density in RH or CH batches in a low-temperature hot press and the cellulosic materials are burned. From the above contamination estimates, nearly all the ash and scrubber residues from the GPT are RH; therefore all the ash and scrubber residues are melted to 90% of theoretical density as RH.

For incineration,

1 kg combustibles → 0.03 kg of ash + 5.7E-4 m^3 concentrated scrubber solution.

It is assumed that the scrubber solution contains the following salt concentration (U.S. DOE 1979:4.4.6). (These equations describe the assumptions made; they are not chemically balanced.)

$NaHCO_3$	0.7 M	$NaHCO_3 \rightarrow Na_2O + H_2CO_3$
Na_2SO_3/Na_2SO_4	0.06 M	$aNa_2SO_3 + bNa_2SO_4 \rightarrow (a+b)Na_2SO_3$
		$Na_2SO_3 \rightarrow Na_2O + SO_3$
particles	0.2 g/L	assumed oxides

The residue composition from 1 L of concentrated scrubber solution is:

	Moles	Weight, g
Na_2O	0.41	25.4
SO_3	0.06	4.8
Particles	--	0.2
		30.4

Therefore, 1 m^3 of concentrated scrubber solution is equivalent to 30.4 kg of concentrated scrubber residues, or 1 kg of combustibles (without PVC) is incinerated to produce 0.0173 kg of scrubber residues.

B.6 OPTION 5 - MAXIMUM VOLUME REDUCTION WITH DECONTAMINATION

The processing emphasis of this option is on decontamination. The LLW resulting from the decontamination is packaged in 160-gal containers. In Suboption 5A, the solids removed from the hull decontamination are incorporated into HLW glass, and the diameter of the HLW canister is increased to accommodate the additional HLW without increasing the number of HLW canisters. In Suboption 5B, the solids from the hull decontamination solution are hot pressed. Secondary wastes from other decontamination operations are also incorporated in HLW glass. These latter quantities are small; thus it is assumed that this small quantity of HLW (a 2.8% increase in the amount of HLW glass formed) can be added to the existing HLW without requiring an increase in the canister size or in the number of HLW canisters. The HLW glass is assumed to have a density of 2,700 kg/m^3.

The hulls are cryogenically cracked prior to decontamination. A packing density of 1,360 kg/m^3 is assumed for the cracked hulls. During decontamination, 7 wt% of the hulls is removed. It is assumed that half of the material removed is Zr and half is ZrO_2. The hull decontamination slurry contains Zr, ZrO_2, and Al_2O_3 abrasives. The volume of alumina in the decontamination slurry is 5 cm^3/kg of decontaminated hulls. The density of the alumina is 1,800 kg/m^3. The water in the decontamination slurry is then boiled off. In Option 5A, the solids from the decontamination slurry (Zr, ZrO_2, Al_2O_3) are loaded into HLW glass at 20 wt%. In Option 5B the Zr/ZrO_2 solids are hot pressed to 90% theoretical density in a high-temperature hot press. The density of Zr is 6,450 kg/m^3, and the density of ZrO_2 is 5,600 kg/m^3.

The fuel hardware, failed equipment, metal filter frames, and metallic GPT-SAC waste are decontaminated by vibratory finishing. It is assumed that during decontamination, 50 g of metal fines are removed per m^2 of decontaminated surface area, and that the decontamination solution contains 0.35 kg of NaOH per m^2 of decontaminated surface area. In estimating the surface areas

of the metals to be decontaminated, it is assumed that the metals have a density of 7,800 kg/m^3; that the failed equipment has an average thickness of 0.0064 m (1/4 in.); and that the fuel hardware, metal filter frames, and metallic GPT-SAC waste have an average thickness of 0.0032 m (1/8 in.). The decontamination slurries contain Fe and NaOH. After the water is removed from the decontamination slurries, the Fe is converted to Fe_2O_3. The Fe_2O_3 is loaded in HLW glass at 33 wt%. It is assumed that the addition of NaOH replaces the Na in the glass frit additive to the HLW glass mixture and does not increase the HLW volume.

After decontamination the packing density of the low-level hardware is assumed to be 1,000 kg/m^3.

Thirty wt% (or vol%) of the failed equipment is assumed to be nondecontaminable and is therefore compacted. A volume reduction factor of 1.67 is assumed, as in Option 2. The decontaminable failed equipment is size reduced prior to decontamination. This size reduction gives a volume reduction factor of 2.

The filters are shredded and incinerated to burn the wood and adhesive. The metal frames are removed from the ash and media and decontaminated by vibratory finishing. The decontaminated metal frames are assumed to have a density similar to that of cut-up glove boxes (530 kg/m^3). The decontamination solution residues (containing iron oxide and caustic), ash, and scrubber solution solids (from incineration; their composition is the same as in Option 4) are loaded into HLW glass at 33 wt%. The filter media are mixed with the total production of HLW glass without the use of incremental additives.

The GPT-SAC waste is sorted by material type. Thirty wt% of the metals are considered nondecontaminable. These metals are compacted with the nondecontaminable failed equipment. The nondecontaminable GPT-SAC waste is assumed to be compacted to the same density as the GPT-SAC waste (1,350 kg/m^3) in Option 2. The compacted waste is packaged in 160-gal containers.

The plastic and rubber is 33 wt% of the combustible portion of the GPT-SAC waste. The plastic and rubber are decontaminated by vibratory finishing, as are the metals. It is assumed that the plastic and rubber have an average

thickness of 0.5 mm (0.02 in.) and that the decontamination solution contains 0.35 kg NaOH for every m^2 of plastic and rubber decontaminated. It is assumed that the LLW plastic and rubber is packaged at the same density (105 kg/m^3) as the GPT-SAC waste in Option 1.

The cellulosic materials in GPT-SAC waste are incinerated to ash. The scrubber solution from the incineration is decontaminated and the low-level liquids and scrubber solution salt are cemented using the following recipe:

6.4 wt% NaCl and other salts
37.3 wt% water
56.3 wt% cement
density 1,820 kg/m^3.

The cementation TRUW is packaged in 55-gal drums. The solids ($Fe(OH)_3$) from the decontamination of the scrubber solution are loaded into HLW glass with the ash at 33 wt%.

The decontaminable metallic GPT-SAC waste (70 wt% of the metals) is decontaminated in the same way as the decontaminable failed equipment. The low-level metallic GPT-SAC waste is assumed to have the same density (105 kg/m^3) as the untreated GPT-SAC waste. The nondecontaminable waste is compacted to the same density (1,350 kg/m^3) as the compacted GPT-SAC waste in Option 2.

The TRU fluorinator solids are converted to LLW by blending them with other non-TRU fluorinator solids.

B.7 OPTION 6 - NONCOMBUSTIBLE WASTE FORMS

The hulls and hardware and failed equipment are melted as in Option 4. The SAC waste is sorted into noncombustibles and combustibles. The noncombustible GPT-SAC waste (which is primarily metal) is treated in the same manner as in Option 4. The combustible GPT-SAC waste and filters are shredded and burned. The ash, media, filter metal, and scrubber residue solids are cemented. Quantities converted from CH to RH waste are estimated as before.

The incineration of 1 kg of combustibles produces 0.03 kg of ash and 5.7E-4 m^3 of concentrated scrubber solution. Therefore, the incineration of 1 kg of wood filters and adhesives is equivalent to 0.0173 kg of solids (see

Option 4). The scrubber solution from the incineration of GPT-SAC waste containing PVC will also contain NaCl. One-third of the combustible GPT-SAC waste is plastic and rubber (Darr 1983). PVC is 30 wt% of the plastic and rubber (Allied-General Nuclear Services 1978:E-2) where 57 wt% of the PVC is taken to be Cl^- (which is converted to NaCl). Therefore, burning 1 kg of the combustible GPT-SAC waste results in 0.094 kg of NaCl in the scrubber solution.

The following cement recipe is used:

50 wt% cement

20 wt% water

5 wt% salt (NaCl)

10 wt% soft waste (media, ash)

15 wt% hard waste (metals, fluorinator solids)

density 2,000 kg/m^3.

The fluorinator solids are cemented at 30 wt% waste loading. It is assumed that the cementing of the fluorinator solids will result in LLW, which is packaged in 160-gal containers.

B.8 REFERENCES

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

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

McKee, R. W., L. L. Clark, P. M. Daling, J. F. Nesbitt, and J. L. Swanson. 1984. "Economic Analysis of Waste Management System Alternatives for Reprocessing Wastes." Waste Management 1984, pp. 383-393. University of Arizona, Tucson.

Schneider, V. W., and F. W. Ledebrink. 1983. "Cementation of TRU-Wastes by a New Process, Properties of the Products." Presented at the Second International Symposium on Ceramics in Nuclear Waste Management, Chicago, Illinois, April 1983.

U.S. Department of Energy. 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028, Volume 2 of 5, U.S. DOE, Washington, D.C.

APPENDIX C

ADDITIONAL INFORMATION ON REGULATIONS AND TRUW DEFINITIONS

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ADDITIONAL INFORMATION ON REGULATIONS AND TRUW DEFINITIONS

C.1 REGULATIONS

The EPA regulation 40 CFR 190 (U.S. EPA 1984a) is the basic federal regulation regarding environmental radiation protection for the operation of uranium nuclear fuel cycle facilities. This regulation states that the dose equivalent to any member of the public for expected performance of operations in the nuclear fuel cycle shall not exceed 75 mrem/yr to the thyroid or 25 mrem/yr to the whole body or to any other organ. If an individual is exposed to radiation sources from two or more activities in the nuclear fuel cycle, any one activity can expose the individual to only a prorated fraction of this total dose. The EPA has included these numerical limits in Subpart A of their proposed regulation 40 CFR 191 (U.S. EPA 1985) for application to expected performance in the operational aspects of waste management (i.e., treatment, storage, and filling and pre-sealing of a repository). The limits are not intended to apply to unexpected performance, to the post-closure disposal time period, or to transportation.

Guidance for ALARA exposure for operating nuclear power reactors is given in Appendix I of 10 CFR 50 (U.S. NRC 1984a). This guidance, which is not specified as being applicable to nonreactor facilities, suggests 5 to 10 mrem/yr for each of several exposure pathways. Regulation 10 CFR 72 (U.S. NRC 1984b) for offsite spent fuel storage facilities specifies an ALARA-based dose limit of 5 mrem/yr to members of the public.

The basic regulations for radiation protection of the public during transportation are covered in 10 CFR 20 (U.S. NRC 1984c). Specific regulations have been issued by the DOT in 49 CFR 171-178 (U.S. DOT 1984) and by the NRC in 10 CFR 71 (U.S. NRC 1984d). The regulations specify packaging requirements, radiation limits, labeling requirements, handling procedures, and security procedures. Containment is the principal performance requirement for transportation of TRUW, and it is generally provided by the outer transportation packaging (i.e., the cask for RH TRUW, and the TRUPACT packaging for

CH TRUW). The outer packaging must maintain containment under accident conditions (as well as normal conditions). The transportation packaging must endure severe physical tests without loss of containment. The most important of these tests are, in sequence: impact, puncture, fire, and submersion in water. These tests are sufficiently stringent that they encompass the performance needs for all but the most severe accidents, for which the probability of occurrence is very low.

For shipments containing more than 20 Ci of plutonium (which would include much of the TRUW), the NRC regulations require that the packaging system (i.e., outer cask and inner packagings such as the canister or an overpack of the canister within the outer packaging) must retain two levels of containment during test conditions. However, the NRC regulations do allow for the exemption of some materials on a case-by-case basis (which currently includes spent fuel). Potential exemption from this requirement would probably depend on the expected releases of waste materials during severe accidents, which in turn would be related to the waste form characteristics in combination with the canister, the liners/spacers inside the transportation packaging, and the transportation packaging. In any case, the waste canister can be less rugged than the cask, which will absorb nearly all of the accident environment. It is assumed in this study that the necessary level of containment for transporting the wastes is provided by the transportation packagings and the canisters, in combination with reusable liners/spacers within the transportation packagings.

C.2 DEFINITION OF TRUW

The following definition of TRUW is given in the fifth working draft of proposed 40 CFR 191:

> Transuranic wastes, as used in this part, means wastes containing more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than 20 years, per gram of waste except for: (1) high-level radioactive wastes; (2) wastes that the Department [DOE] has determined, with the concurrence of the Administrator [of EPA], do not need the degree of isolation needed by this Part; or (3) wastes that the Commission [NRC] has approved for disposal on a case-by-case basis in accordance with 10 CFR 61.

This definition generally includes all of the actinides with atomic numbers higher than that of uranium (92) that are present in significant quantities in spent nuclear fuel, with the exclusion of ^{241}Pu and ^{244}Cm. It excludes all alpha-emitting actinides lighter than uranium (isotopes of protactinium, thorium, actinium, radium, francium, radon, astatine, polonium, and bismuth), even though some of these are present in important quantities in spent fuel and some are potentially important dose contributors in waste management.

The NRC has yet to specify a definition of TRUW to be used for waste management purposes. However, the NRC has identified TRUW as waste containing greater than 100 nCi of transuranium elements per gram of waste, with transuranium elements defined as those having atomic numbers greater than 92. They also state that transuranium elements include uranium and plutonium.

The NRC has defined HLW and LLW in 10 CFR 60 (U.S. NRC 1984e) and 10 CFR 61 (U.S. NRC 1984f), respectively, and TRUW must fall somewhere between these definitions. HLW is defined by its source: "(1) irradiated reactor fuel, (2) liquid wastes resulting from operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which such liquid wastes have been converted." Low-level wastes are those "that are acceptable for disposal in a land disposal facility." Low-level waste is "waste that is radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or byproduct material." Wastes that are not acceptable for shallow land burial are then identified in 10 CFR 61 by specifying maximum concentrations of TRU nuclides with half-lives greater than 5 years of 100 nCi/g, the maximum amount of ^{241}Pu of 3,500 nCi/g, and the maximum amount of ^{242}Cm of 20,000 nCi/g of waste. (The correction for the beta-emitter ^{241}Pu allows for the alpha decay of its daughters; the correction for the short-lived alpha-emitter ^{242}Cm allows for decay of its long-lived ^{241}Pu alpha-emitting daughters.) Numerical limits are also given for non-TRU radionuclides.

The Waste Acceptance Criteria for WIPP (Westinghouse Electric Company 1984) also include ^{233}U as a transuranic nuclide. The general definition in DOE Order 5820 (draft February 6, 1984) (U.S. DOE 1984) is slightly different;

it states that transuranic waste is "radioactive waste that at the end of the institutional control periods is contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and concentrations greater than 100 nCi/g."

All of these definitions are similar. For this study, the definition given in the fifth working draft of EPA's 40 CFR 191 regulation is used.

C.3 WASTE FORM REQUIREMENTS

Waste form requirements for TRUW have yet to be specified. The NRC has requirements for releases from the engineered barriers (including waste forms) for geologic disposal of HLW and TRUW in 10 CFR 60 and for LLW forms for shallow-land burial in 10 CFR 61. The DOE has requirements for defense TRUW to be disposed of at WIPP (Westinghouse Electric Company 1984). The EPA has only some proposed general requirements for release of radionuclides from TRUW to the accessible environment in the fourth and fifth working drafts of 40 CFR 191 (U.S. EPA 1984b, 1985). The requirements that may be related to waste forms in these regulations are given in Table C.1 and are discussed in Section 4.

The release limits from a deep geologic (basalt) repository to the accessible environment for spent fuel, HLW, and/or TRUW proposed by the EPA in the fourth working draft of 40 CFR 191 are given in Table C.2.

TABLE C.1. Regulations/Criteria Related to TRUW Form/Container Requirements

No.	Characteristic	10 CFR 60, HLW and TRUW	10 CFR 61, LLW (generally for classes B&C)	40 CFR 191, HLW & TRUW	WIPP WAC and TRUW	Composite Bases from 10 CFR 61, 40 CFR 191, and WIPP WAC
1	Canister	Retrievable within 50 years; sealed; maintain containment during transportation; pass transportation type A tests; emplacement, retrieval	No cardboard or fiberboard; 300-year life plus other requirements in branch technical position paper if waste form does not meet requirements below		Noncombustible; 25+ year life; <25,000 lb; <12' x 8' x 8.5' CH; 8,000 lb RH; 26" x <10' RH	Noncombustible; 25+ year life; 300 year life with poor waste forms (see "other" below); pass Type A transportation requirements; for CH TRUW, <12' x 8' x 8.5' and <25,000 lb; for RH TRUW <26" dia x 10' and <8,000 lb; maintain containment during transportation, emplacement, retrieval
2	Package characteristics	Chemical-physical-nuclear characteristics compatible with repository; 300-1000 year life for package				Chemical-physical-nuclear characteristics compatible with repository
3	Package considerations	Solubility; oxidizing/reducing potential; corrosion; hydriding, gas generation; thermal stress; radiolysis; retardation; leaching; fire/explosion hazards; synergistic interactions				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	Solid; particulates to be consolidated; not dispersible	Free-standing monoliths (for Class A solidified liquids only); other requirements in branch technical position paper (see item 18 and item 4, Column 7) if no 300-year container		<1%/can must be <10 μm particles and <15%/can must be <200 μm particles; sludges OK if corrosion protection; no corrosive materials	Resistant to radiation (1E8 Rad γ); resistant to biodegradation test; resistant to leaching; resistant to breakdown from water immersion; resistant to breakdown test; compressive strength >50 psi; not dispersible; <1%/can must be <10 μm particles
5	Waste form combustibility	Must be noncombustible unless shown that fire will not compromise safety			OK but must be in noncombustible canister and labeled	Must be noncombustible unless shown that fire will not compromise safety
6	Free liquid content	None that could compromise isolation (in package)	<0.5% of weight per ANS 55.1; needs double the minimum amount absorbent		None in can; sludges OK if container is corrosion protected	<0.5 wt%; need double the minimum amount absorbent; sludges OK if container is corrosion protected
7	Explosives content		Not readily capable of reaction		None allowed	None allowed

TABLE C.1. (contd)

No.	Characteristic	10 CFR 60, HLW and TRUW	10 CFR 61, LLW (generally for classes B&C)	40 CFR 191, HLW & TRUW	WIPP WAC and TRUW	Composite Bases from 10 CFR 61, 40 CFR 191, and WIPP WAC
8	Toxic gases, vapors		None allowed, except for gaseous radionuclides		No toxic materials or poisons A, B unless co-contaminants	None allowed except for gaseous radionuclides
9	Pyrophoric material content	Must not contain amounts that could compromise waste isolation	None allowed		None if nonradioactive; radionuclides <1% and must be dispersed	Allowed only if intimately associated with radionuclides, and then radionuclides must be <1 wt% of waste
10	Gaseous waste		Pressure <1.5 atm at 20°C; <100 Ci/container of gaseous radionuclides			Pressure <1.5 atm at 20°C; <100 kg/m^3 in other containers
11	Gas generation				<100-220 kg/m^3 organic in waste; <10 $moles/m^3$ room/yr gas generation rate by all mechanisms	<220 kg/m^3 organic in 55 gal drums; <100 kg/m^3 in other containers
12	Hazardous, biologically pathogenic, infectious material		Reduce nonradiological hazard as low as practicable; see also branch position paper requirements for LLW below			Reduce nonradiological hazard to as low as practicable; see also branch position paper requirements for LLW below
13	Structural stability		Form or container must be structurally stable in disposal environment; see branch position paper below			Form or canisters must be structurally stable in disposal environment; see also branch position paper for LLW below
14	Void spaces		Reduce to extent practical			Reduce to extent practical
15	Release rate from repository to environment	From engineered barrier, <1E-5/yr of 1000 year inventory; not applicable to radionuclides released <0.1% of calculated total		In 10,000 years, release values less than in table with probability <0.1; alpha radionuclides to aquifer in 1,000 years shall be <15 pCi/L		Probability <0.1 that release values in 10,000 years will exceed those in EPA table; alpha radionuclides to aquifer in 1000 years shall be <15 pCi/l; from engineered barrier <1E-5/yr of 1000 year inventory; not applicable to radionuclides released <0.1% of calculated total release rate
16	Dose to public			<25/75/25 mrem/yr + ALARA; <4 mrem/yr $\beta + \gamma$ from radionuclides in aquifer		<25/75/25 mrem/yr + ALARA; <4 mrem/yr $\beta + \gamma$ from radionuclides in aquifer
17	Identification	Permanent and unique				Permanent and unique

TABLE C.1. (contd)

No.	Characteristic	10 CFR 60, HLW and TRUW	10 CFR 61, LLW (generally for classes B&C)	40 CFR 191, HLW & TRUW	WIPP WAC and TRUW	Composite Bases from 10 CFR 61, 40 CFR 191, and WIPP WAC
18	Other		Branch technical position paper (U.S. NRC 1983) gives details on waste form requirements: compressive strength >50 psi per ASTM C39 after all tests:- Expose to 1E+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 -40°C, 30 times (ASTM 8554, Section 3) - Destructive analysis to assure homogeneity Or for 300-year LLW container - Strength with 120 lb/ft^3 overburden - Resistant to 1E+8 Rad - Resistant to biodegradation test as above - Resistant to thermal cycling as above - Positive steel - Contents inspectable - Passive vent - Withstand 3 G lifting load		CH <3.5 W/m^3; RH <300 W/can; <200 g fissile/55 gal drum; Dose CH <200 mrem/hr; Dose RH <100 rem/hr; <5 g ft^3 fissile RH	For LLW forms, compressive strength <50 psi after all tests: - Expose to 1E+8 Rad - Resistant to biodegradation test - Resistant to 90 day leach test (leachability index >6 per ANS 16.1) - Resistant to immersion 90 days - Resistant to thermal cycling 60° to -40°C - Destructive analysis to assure homogeneity) Or for 300-year LLW container - Strength with 120 lb/ft^3 overburden - Resistant to 1E+9 Rad - Resistant to thermal cycling as above - Resistant to biodegradation test as above - Positive steel - Contents inspectable - Passive vent - Withstand 3 g lifting load CH <3.5 W/m^3; RH <300 W/can; <200 g fissile/55-gal drum; Dose CH <200 mrem/hr; Dose RH <100 rem/hr; <5 g/ft^3 fissile RH

TABLE C.2. Release Limits for Containment Requirements (cumulative releases to the accessible environment for 10,000 years after disposal) (U.S. EPA 1985)

Radionuclide	Release Limit (curies)	Radionuclide	Release Limit (curies)
Americium-241	100	Plutonium-242	100
Americium-243	100	Radium-226	100
Carbon-14	100	Strontium-90	1,000
Cesium-135	1,000	Technetium-99	10,000
Cesium-137	1,000	Tin-126	1,000
Neptunium-237	100	Any other alpha-emitting radionuclide	100
Plutonium-238	100		
Plutonium-239	100	Any other radionuclide that does not emit alpha particles	1,000
Plutonium-240	100		

Note 1: The Release Limits in Table C.2 apply to the amount of wastes in any one of the following:

(a) an amount of spent nuclear fuel containing 1,000 metric tons of heavy metal (MTHM);
(b) the high-level wastes, as defined by 191.02(e)(1), generated from each 1,000 MTHM;
(c) each 100,000,000 curies of gamma- or beta-emitting radionuclides with half-lives less than 100 years that are identified by the Commission as high-level waste in accordance with 191.02(e)(2);
(d) each 1,000,000 curies of other radionuclides (gamma- or beta-emitters with half-lives greater than 100 years or any alpha-emitters) that are identified by the Commission as high-level waste in accordance with 191.02(e)(2); or
(e) an amount of transuranic wastes, as defined by 191.02(f), containing one million curies of alpha-emitting transuranic radionuclides.

To develop Release Limits for a particular disposal system, the quantities in Table C.2 shall be adjusted for the amount of wastes included in the disposal system. For example:

(a) If a particular disposal system contained the high-level wastes from 50,000 MTHM, the release limits for that system would be the quantities in Table C.3 multiplied by 50 (50,000 MTHM divided by 1,000 MTHM).
(b) If a particular disposal system contained three million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table C.3 multiplied by three (three million curies divided by one million curies).
(c) If a particular disposal system contained both the high-level wastes from 50,000 MTHM and 5 million curies of alpha-emitting transuranic wastes, the release limits for that system would be the quantities in Table C.3 multiplied by 55:

$$\frac{50{,}000 \text{ MTHM}}{1{,}000 \text{ MTHM}} + \frac{5{,}000{,}000 \text{ curies TRU}}{1{,}000{,}000 \text{ curies TRU}} = 55$$

Note 2: In cases where a mixture of radionuclides is projected to be released, the limiting values shall be determined as follows: For each radionuclide in the mixture, determine the ratio between the cumulative release quantity projected over 10,000 years and the limit for that radionuclide as determined for Table C.2 and Note 1. The sum of such ratios for all the radionuclides in the mixture may not exceed one.

For example, if radionuclides A, B, and C are projected to be released in amounts Q_a, Q_b, and Q_c, and if the applicable Release Limits are RL_a, RL_b, and RL_c, then the cumulative releases over 10,000 years shall be limited so that the following relationship exists:

$$\frac{Q_a}{RL_a} + \frac{Q_b}{RL_b} + \frac{Q_c}{RL_c} \leq 1$$

C.1 REFERENCES

U.S. Department of Energy. 1984. Radioactive Waste Management, DOE Draft Order 5820, February 6, 1984. U.S. DOE, Washington, D.C.

U.S. Department of Transportation. 1984. Code of Federal Regulations, Title 49, Transportation (Subchapter C - Hazardous Material Regulations); Part 171, General Information, Regulations and Definitions; Part 172, Hazardous Materials Table and Hazardous Materials Communications Regulations; Part 173, Shippers General Requirements for Shipments and Packagings; Part 174, Carriage by Rail; Part 177, Carriage by Public Highway; Part 178, Shipping Container Specifications. Revised January 1, 1982. U.S. DOT, Washington, D.C.

U.S. Environmental Protection Agency. 1984a. Code of Federal Regulations, Title 40, Protection of Environment; Part 190, Environmental Protection Standards for Nuclear Power Operations. Revised January 1, 1982. U.S. EPA, Washington, D.C.

U.S. Environmental Protection Agency. 1984b. Fourth Working Draft. Code of Federal Regulations, Title 40, Protection of Environment; Part 191, Environmental Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes. April 17, 1985. U.S. Public Document Room, Washington, D.C.

U.S. Environmental Protection Agency. 1985. Fifth Working Draft. Code of Federal Regulations, Title 40, Protection of Environment; Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes. March 21, 1985. U.S. Public Document Room, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1983. Low-Level Licensing Branch Technical Position on Radioactive Waste Classification. May 1983, Revision D. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984a. Code of Federal Regulations, Title 10, Energy; Part 50, Domestic Licensing of Production and Utilization Facilities. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984b. Code of Federal Regulations, Title 10, Energy; Part 72, Licensing Requirements for the Storage of Spent Fuel in an Independent Spent Fuel Storage Installation (ISFSI). U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984c. Code of Federal Regulations, Title 10, Energy; Part 20, Standards for Protection Against Radiation. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984d. Code of Federal Regulations, Title 10, Energy; Part 71, Packaging and Transportation of Radioactive Material. U.S. Federal Register, Vol. 48, p. 35607, August 5, 1983; p. 38449, August 24, 1983. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984e. Code of Federal Regulations, Title 10, Energy, Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories (Subpart E: Technical Criteria). Final Rule. U.S. Federal Register, Vol. 48, No. 120, June 21, 1983, pp. 28194-28229. U.S. NRC, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1984f. Code of Federal Regulations, Title 10, Energy; Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, Final Rule. U.S. Federal Register, Vol. 47, December 27, 1982 (Effective January 26, 1983), p. 57463. U.S. NRC, Washington, D.C.

Westinghouse Electric Company. 1984. TRU Waste Acceptance Criteria for the Waste Isolation Pilot Plant. WIPP-DOE-069, Rev. 2, Draft C, Albuquerque, New Mexico.

APPENDIX D

PROCESSING, TRANSPORTATION, AND DISPOSAL COST ESTIMATES

APPENDIX D

PROCESSING, TRANSPORTATION, AND DISPOSAL COST ESTIMATES

D.1. PROCESSING COST ESTIMATE

The capital and operating cost estimates for each treatment option studied in this report were taken from McKee et al. (1984) when available. For those operating costs not available in the McKee study, the capital and operating costs were approximated by the authors. Table D.1 gives the capital cost estimates and Table D.2 gives the operating cost estimates for each TRUW treatment option. All cost estimates are based on undiscounted 1983 dollars.

Included in the operating cost are the cost of replacing the used containers and the cost of purchasing containers to package the processed waste. Table D.3 describes the containers used in this study and gives the costs of these containers.

D.2 TRANSPORTATION COST ESTIMATE

This section describes the cost estimates for transporting the wastes in two subsections; the first considers TRUW and HLW transported to a repository, and the second considers LLW transportation costs.

D.2.1 TRUW and HLW Transport Cost Estimation

The TRUW and HLW transport cost estimate for this report is based on a transportation cost analysis in the McKee study. The transportation costs for TRUW consisted of a cask leasing fee and freight charges. For this study it was simplest to calculate the transportation costs on a per shipment basis. Table D.4 gives the parameters needed to determine the number of drums a shipment can carry. For example, for RH 55-gal drums with a surface dose of less than 1 R/hr, a shipment consists of three casks. Each cask contains 14 drums. Therefore each shipment transports (3 casks) (14 drums/cask), or 42 55-gal drums.

TABLE D.1. Capital Costs for the Six TRUW Treatment Options

Option	Facility	Capital Cost for 1,500 MTU/yr Reprocessing, $M
1	HLW vitrification	170[a]
	TRUW storage	32[b]
	Waste assay	34[a]
2	HLW vitrification	170[a]
	TRUW storage	24[b]
	Waste assay	34[a]
	TRUW treatment	40[c]
3	HLW vitrification	170[a]
	TRUW storage	33[b]
	Waste assay	34[a]
	TRUW treatment	40[c]
4	HLW vitrification	170[a]
	TRUW storage	21[b]
	Waste assay	34[a]
	TRUW treatment	93[c]
5A	HLW vitrification	200[a,c]
	TRUW storage	21[b]
	Waste assay	34[a]
	TRUW treatment	115[c]
5B	HLW vitrification	170[a]
	TRUW storage	21[b]
	Waste assay	34[a]
	TRUW treatment	145[c]
6	HLW vitrification	170[a]
	TRUW storage	21[b]
	Waste assay	34[a]
	TRUW treatment	95[c]

(a) Cost estimates are from McKee et al. (1984).

(b) Cost estimates are based on those in McKee et al. (1984), which were then scaled to appropriate capacities using the following exponential scaling factors: 0.5 for processing facilities, 0.6 for RH storage, and 0.8 for CH storage.

(c) Estimated by the authors.

TABLE D.2. Operating Costs Based on 1,500 MTU/yr for the Six TRUW Treatment Options[a]

Option	Facility	Operating Cost, $M/yr	Canister Cost, $M/yr	Total Operating Cost, $M/yr
1	HLW vitrification[b]	5.8	5.3	11.1
	TRUW storage[b]	1.9	5.9	7.8
	Waste assay[b]	2.0	--	2.0
	Total			20.9
2	HLW vitrification[b]	5.8	5.3	11.1
	TRUW storage[b]	1.4	1.1	2.5
	Waste assay[b]	2.0	--	2.0
	TRUW treatment[c]	2.4	--	2.4
	Total			18.0
3	HLW vitrification[b]	5.8	5.3	11.1
	TRUW storage[b]	2.0	1.3	3.3
	Waste assay[b]	2.0	--	2.0
	TRUW treatment[c]	0.8	--	0.8
	Total			17.2
4	HLW vitrification[b]	5.8	5.3	11.1
	TRUW storage[b]	1.3	0.4	1.7
	Waste assay[b]	2.0	--	2.0
	TRUW treatment[c]	6.4	--	6.4
	Total			21.2
5A	HLW vitrification[b]	6.8	6.6	13.4
	TRUW storage[b]	1.3	2.1	3.3
	Waste assay[b]	2.0	--	2.0
	TRUW treatment[c]	7.3	--	7.3
	Total			26.0
5B	HLW vitrification[b]	5.8	5.3	11.1
	TRUW storage[b]	1.3	2.2	3.5
	Waste assay[b]	2.0	--	2.0
	TRUW treatment[c]	9.1	--	9.1
	Total			25.7
6	HLW vitrification[b]	5.8	5.3	11.1
	TRUW storage[b]	1.3	0.5	1.8
	Waste assay[b]	2.0	--	2.0
	TRUW treatment[c]	5.7	--	5.7
	Total			20.6

(a) Costs are for one reprocessing plant operating at a rate of 1,500 MTU/yr.

(b) Cost estimates are from McKee et al. (1984). Costs are scaled to appropriate capacities using the following exponential scaling factors based on capacity: 0.6 for RH storage and 0.8 for CH storage.

(c) Fraction of capital cost representing operating cost (minus canister and drum costs) estimated by authors based on analysis of operating costs in DOE/ET-0028 (U.S. DOE 1979).

TABLE D.3. Container Description and Cost

Container/Drum Size	Material Type	Cost (mid-1983 $/container)
55-gal drum	Galvanized mild steel	60[a]
55-gal drum	Stainless steel	300[b]
80-gal drum	Galvanized mild steel	120[c]
53-gal canister	Stainless steel	8,100[d,e]
160-gal canister	Stainless steel	8,100[d]
160-gal canister	Mild steel	2,000[b,f]
160-gal canister	Mild steel	4,000[g]
600-gal canister	Stainless steel	14,500[d,h]
600-gal canister	Mild steel	3,600[c]

(a) Rockwell-Hanford Operations costs for WIPP qualified containers.
(b) Estimated from cost of other container in this size using cost of fabricated stainless steel equal to 4 times the cost of fabricated mild steel.
(c) Estimated by authors, based on costs for 55-gal drum.
(d) From McKee et al. (1984).
(e) A canister is used for HLW (McKee et al. 1984).
(f) This cost per canister is also used for LLW Class C. Cost is based on scaledown from larger, commercially available canisters.
(g) Cost is for hot pressing canisters, to include cost of compressible inner canisters.
(h) A canister is used for Option 1 because of process needs.

The cask leasing charges are from the McKee et al. (1984) study and the freight charges are from a study by McNair et al. (1984). These transport charges are given in Table D.5.

As an example of how the transport costs were calculated, assume that some RH 55-gal drums with a surface dose <1 R/hr are to be transported. A shipment of these drums consists of 42 drums. The cask leasing fee for 55-gal drums is $200/day/cask. The round-trip transit time is 24 days. Since each shipment contains 3 casks, the cask leasing fee per shipment = ($200/day/cask) (24 days) (3 casks/shipment), or $14,400/shipment of 42 RH 55-gal drums with a surface dose less than 1 R/hr. It is assumed that each shipment is accompanied by an escort for $1,900 per shipment. The cost per shipment of transporting a filled

TABLE D.4. Transportation Parameters for TRUW and HLW

Waste and Container Type	Number of Containers/ Transport Packaging	Number of Transport Packaging/ Rail Shipment	Type of Rail Cask	Transport Packaging Weight, kg/cask[e] Packaging Empty	Packaging Loaded
RH TRUW					
55-gal drum, <1 R[b]	14	3	CNS14-170[c]	72,600	90,700
55-gal drum, >1 R[b]	7	3	CNS7-100[c]	72,600	90,700
80-gal drum, <1 R[b]	10	3	CNS14-170[c]	72,600	90,700
80-gal drum, >1 R[b]	5	3	CNS7-100[c]	72,600	90,700
160-gal canister	7[d]	1	DHLW-rail[e]	80,500	90,700
600-gal canister	1	1	Cladding hulls-rail[c]	70,800	78,000[f]
CH TRUW					
55-gal drum	54	2	TRUPACT[b]	36,300	63,500
80-gal drum	42	2	TRUPACT[b]	36,300	63,500
160-gal canister	18	2	TRUPACT[b]	36,300	63,500
600-gal canister	1	1	Cladding hulls-rail[b]	70,800	78,000[f]
HLW					
200-L CHLW canister	12	1	CHLW-rail[b]	70,000	80,300
320-L CHLW canister	7	1	CHLW-rail[b]	70,000	80,300

(a) Source of these packaging weights is Wilmot et al. (1983), unless specified otherwise.
(b) <1 R means surface dose rate <1 R/hr and >1 R means surface dose rate >1 R/hr.
(c) Capacity of rail cask is given by Wilmot et al. (1983). Cavity is 56 inches in diameter.
(d) It is assumed that a DHLW cask can hold seven 160-gal canisters.
(e) Capacity of rail cask is given by Wilmot et al. (1983). Cavity is 88 inches in diameter.
(f) The maximum weight of a 600-gal canister from any of the TRUW treatment processes is 6,700 kg. This is added to the empty weight of the 600 gal transport packaging weight (70,800 kg) to obtain the loaded weight of 78,000 kg.

cask containing 55-gal drums of waste and then returning the empty cask is $30,560/shipment. Therefore the total cost of transporting the waste is the freight cost of $32,460 ($1,900 + $30,560) plus the cask leasing fee of $14,400, for a total of $46,860.

Tables D.6 through D.9 give the cost of transporting the waste generated from each treatment option. The costs are given by waste type on a basis of

TABLE D.5. Cask Leasing and Freight Charges for Transporting TRUW and HLW

Waste and Container Type	Cask Leasing Charges			Freight Charges[a]			Cask and Freight Charge, $/shipment	Number of Containers/ Shipment
	Cask Leasing Rate, $/day/cask	Round Trip Transit Time, days	Cask Leasing Fee, $/shipment	Escort, $/shipment	Cask and Waste,[e] $/shipment	Total Freight Fee, $/shipment		
RH TRU								
55-gal drum, <1 R[b]	200	24	14,400	1,900	30,560	32,460	46,860	42
55-gal drum, >1 R[b]	200	24	14,400	1,900	30,560	32,460	46,860	21
80-gal drum, <1 R[b]	200	24	14,400	1,900	30,560	32,460	46,860	30
80-gal drum, >1 R[b]	200	24	14,400	1,900	30,560	32,460	46,860	15
160-gal canister	2,750[c]	24	66,000	1,900	32,000	33,900	99,900	7
600-gal canister	1,800	24	43,200	1,900	27,790	29,690	72,890	1
CH TRU								
55-gal drum	800	22	35,200	1,900	18,760	20,660	55,860	108
80-gal drum	800	22	35,200	1,900	18,760	20,660	55,860	84
160-gal canister	800	22	35,200	1,900	18,760	20,660	55,860	36
600-gal canister	1,800	24	43,200	1,900	27,790	29,690	72,890	1
HLW								
200-L commercial HLW canister							122,600[d]	12
320-L commercial HLW canister							122,600[d]	7

(a) Based on round trip.
(b) <1 R means the containers have a surface dose rate <1 R/hr, and >1 R means the containers have a surface dose rate >1 R/hr.
(c) It was assumed that the commercial HLW cask could hold seven 160-gal canisters. The cask-leasing fee assumed a capital cost of $2.5 M (Rasmussen 1982) mid-1982 $. This figure was escalated to mid-1983 $ by multiplying it by 1.1, 25% for capital charges, 10% for annual maintenance, and 300 days/yr utilization.
(d) This charge is taken from McKee et al. (1984).
(e) The freight charge to transport the cask containing the weight was obtained by:

(empty weight, kg) (0.181 $/kg) + (loaded weight, kg) (0.192 $/kg)

where the empty and loaded weights are given in Table D.4 and the rates 0.181 $/kg and 0.192 $/kg are shipping rates from McNair et al. (1984).

TABLE D.6. Transport Quantities and Costs for 1,500 MTU Reprocessed Waste/yr for Options 1 and 2[a]

Waste Type and Container Size	Option 1 Number of Containers/yr	Option 1 Transport Cost, $M/yr	Option 2 Number of Containers/yr	Option 2 Transport Cost, $M/yr
Hulls and hardware				
RH, 60 gal	0	0	350.5	5.00
RH, 600 gal	300	21.87	0	0
Failed equipment				
CH, 55 gal	70	0.04	0	0
CH, 160 gal	0	0	21.8	0.03
CH, 600 gal	4	0.29	0	0
RH, 160 gal	0	0	6.9	0.10
RH, 600 gal	4	0.29	0	0
Filters				
CH, 55 gal	50	0.03	0	0
CH, 80 gal	1,114	0.74	0	0
CH, 160 gal	0	0	27.9	0.04
RH, 80 gal, <1 R/hr	108	0.17	0	0
RH, 80 gal, >1 R/hr	25	0.08	0	0
RH, 160 gal	0	0	39.9	0.57
RH, 600 gal	44	3.21	0	0
Fluorinator solids				
RH, 55 gal, <1 R/hr	93	0.10	93	0.10
GPT-SAC waste				
CH, 55 gal	540	0.28	0	0
CH, 160 gal	0	0	41.5	0.06
RH, 55 gal, <1 R/hr	105	0.12	0	0
RH, 55 gal, >1 R/hr	93	0.21	0	0
RH, 160 gal	0	0	64.8	0.92
RH, 600 gal	37	2.70	0	0
HLW	657.9	6.72	657.9	6.72
Total Cost		36.85		13.54

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

TABLE D.7. Transport Quantities and Costs for 1,500 MTU Reprocessed Waste/yr for Options 3 and 4[a]

Waste Type and Container Size	Option 3		Option 4	
	Number of Containers/yr	Transport Cost, $M/yr	Number of Containers/yr	Transport Cost, $M/yr
Hulls and hardware				
RH, 160 gal	0	0	152.3	2.17
RH, 600 gal	343	25.00	0	0
Failed equipment				
CH, 55 gal	70	0.04	0	0
CH, 160 gal	0	0	4.6	0.01
CH, 600 gal	5	0.36	0	0
RH, 160 gal	0	0	0.9	0.01
RH, 600 gal	3	0.22	0	0
Filters				
CH, 55 gal	131.4	0.07	0	0
CH, 160 gal	0	0	3.9	0.01
RH, 55 gal, <1 R/hr	75.5	0.08	0	0
RH, 55 gal, >1 R/hr	53.1	0.12	0	0
RH, 160 gal	0	0	3.7	0.05
Fluorinator solids				
RH, 160 gal	0	0	15.5	0.22
GPT-SAC waste				
CH, 55 gal	170.5	0.09	0	0
CH, 160 gal	0	0	3.7	0.01
RH, 55 gal, <1 R/hr	118.9	0.13	0	0
RH, 55 gal, >1 R/hr	88.6	0.20	0	0
RH, 160 gal	0	0	5.6	0.08
HLW	657.9	6.72	657.9	6.72
Total cost		33.03		9.28

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

TABLE D.8. Transport Quantities and Costs for 1,500 MTU Reprocessed Waste/yr for Option 5[a]

Waste Type and Container Size	Suboption 5A Number of Containers/yr	Suboption 5A Transport Cost, $M/yr	Suboption 5B Number of Containers/yr	Suboption 5B Transport Cost, $M/yr
Hulls and hardware				
LLW, 160 gal	657.9	0.93	657.9	0.93
HLW contribution[a]	79.3[b]	4.58	0.3[b]	~0
RH, 160 gal	0	0	15.2	0.22
Failed equipment				
LLW, 160 gal	16.7	0.0006	16.7	0.0006
HLW contribution[a]	0.05[b]	0.003	0.05[b]	~0
CH, 160 gal	6.5	0.01	6.5	0.01
RH, 160 gal	2.1	0.03	2.1	0.03
Filters				
LLW, 160 gal	35.8	0.001	35.8	0.001
HLW contribution[a]	3.5[b]	0.20	3.5[b]	~0
Fluorinator solids				
LLW, 160 gal	34.0	0.01	34.0	0.01
GPT-SAC waste				
LLW, 160 gal	130.2	0.005	130.2	0.005
HLW contribution[a]	0.3[b]	0.02	0.3	~0
CH, 160 gal	0.7	0.001	0.7	0.001
RH, 55 gal, >1 R/hr	57.4	0.13	57.4	0.13
RH, 160 gal	1.1	0.02	1.1	0.02
HLW	131.6[b]	6.72	131.6[b]	6.72
Total cost		12.6		8.0

(a) Values are shown in more significant figures than the accuracy of the data to maintain consistency of the calculations.
(b) Value is in m^3/yr.

TABLE D.9. Transport Quantities and Costs for 1,500 MTU Reprocessed Waste/yr for Option 6[a]

Waste Type and Container Size	Option 6 Number of Containers/yr	Option 6 Transport Cost, $M/yr
Hulls and hardware		
RH, 160 gal	152.3	2.17
Failed equipment		
CH, 160 gal	4.6	0.01
RH, 160 gal	1.0	0.01
Filters		
CH, 55 gal	113.5	0.06
RH, 55 gal <1 R/hr	36.8	0.04
RH, 55 gal >1 R/hr	36.4	0.08
Fluorinator solids		
LLW, 160 gal	94.6	0.04
GPT, SAC waste		
CH, 55 gal	6.2	0.003
CH, 160 gal	0.3	0.0005
RH, 55 gal >1 R/hr	11.7	0.03
RH, 160 gal	0.8	0.01
HLW	657.9	6.72
Total Cost		9.17

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

1,500 MTU/yr reprocessed. With Suboptions 5A and 5B (Table D.8) additional HLW is generated during TRUW treatment. These HLW quantities are shown separately from the HLW produced from the liquid waste solidification as the HLW contribution by waste type. Transport costs for LLW, included in Tables D.6 through

D.9 for Options 5 and 6, are discussed in Section D.2.2. Table 8.4 summarizes Tables D.6 through D.9 and gives the total transport costs based on 1,500 MTU and 70,000 MTU reprocessed.

D.2.2 LLW Transport Cost Estimation

The LLW produced in Suboptions 5A, 5B and Option 6 is transported by truck to a disposal facility 300 miles away in the eastern U.S. The low-level fuel hardware is highly radioactive and is therefore transported in a commercial cladding hulls cask. The shipment has a round trip transit time of 1.5 days (for a truck traveling 35 mi/hr, 12 hr/day, 600 miles round trip). The cask leasing fee for a commercial hulls cask is $1,275/day (adjusted 16% from 1981 dollars to 1983 dollars) (Wilmot et al. 1983). The freight charges are $2,660/shipment (McNair et al. 1984). Therefore the total transport cost for the decontaminated hardware is $4,570/shipment [($1,275/day x 1.5 days) + $2,660)]. Each shipment contains only one 160-gal container of spent fuel hardware as LLW.

The cost of transporting the other LLW (hulls, failed equipment, filters, fluorinator solids, and GPT-SAC waste) is based on an analysis in DOE/LLW-6Td (EG&G Idaho 1983). Due to its low surface dose rate (see Section D.3.2), it was assumed that the low-level failed equipment, filters, and GPT-SAC waste do not require shielding or a cask. It has a transport cost of $864/shipment (adjusted 16% from 1981 dollars to 1983 dollars). The volume of a shipment of waste not requiring shielding is 14.2 m^3 (500 ft^3). The hulls and fluorinator solids are classified as shielded waste. The cost of transporting shielded waste is $512/$m^3$, plus $870/shipment for leasing the cask. Each shielded waste shipment contains 4.25 m^3 (150 ft^3) of waste. Therefore the cost of transporting shielded waste is $3,040/shipment.

Table D.10 gives the packaged volume of LLW from Options 5 and 6 and the cost of transporting it to a LLW disposal facility. These quantities are also included in Tables D.6 through D.9.

TABLE D.10. Quantities and Transport Costs for LLW[a]

Waste Type and Container Size	1,500 MTU Basis			70,000 MTU Basis
	Packaged Volume, m^3	Number of Shipments	Cost, $M	Cost, $M
Option 5				
Hulls	305	71.7	0.22	10.2
Hardware	93.7	154.6	0.71	33.0
Failed equipment	10.1	0.7	0.0006	0.03
Filters	21.7	1.5	0.001	0.06
Fluorinator solids	20.6	4.8	0.01	0.7
GPT-SAC waste	78.9	5.6	0.005	0.2
Total cost			0.95	44.2
Option 6				
Fluorinator solids	57.3	13.4	0.04	1.9

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

D.3 DISPOSAL COST ESTIMATIONS

The disposal costs assume that the TRUW and HLW are disposed at a repository in basalt and that the LLW is disposed of at a low-level radioactive waste disposal facility.

D.3.1 TRUW and HLW Disposal Cost Estimator

The disposal costs for TRUW and HLW were estimated using a repository cost computer code RECON (Clark 1983), which gives the life-cycle construction and operating costs of a geologic repository. It was assumed that the repository has the capacity for 70,000 MTU of reprocessed waste, that it could accept both TRUW and HLW, that the RH TRUW and HLW are placed remotely into horizontal boreholes, and that the CH TRUW containers are stacked in the corridors with overpack canisters. The computer model includes labor requirements, rates, waste receiving, packing transport, emplacement, rock excavation, backfilling, sealing, and decommissioning. The repository used in RECON is based on the 1983 reference design concept for the BWIP (Kaiser Engineers Inc./Parsons, Brinkerhoff, Quade, and Douglas, Inc. 1983).

Table D.11 gives the cost of disposing the TRUW and HLW listed in Table 7.9. This information is given in Table 8.5 by waste type. Table 8.5 was obtained by dividing the values in Table D.11 by the quantities of containers and drums in Table 7.9, which have been scaled for 70,000 MTU reprocessed.

D.3.2 LLW Disposal Cost Estimation

The LLW disposal facility at Barnwell, South Carolina is the representative LLW disposal facility for this study. The cost schedule (effective January 1, 1984) for disposing LLW at this facility is given in Appendix E.

For Option 5, Table D.12 lists, for each waste type, the parameters needed to obtain unit costs from the LLW disposal cost schedule in Appendix E. (Because the cost schedule in Appendix E is in English units, the discussion in this subsection is as well.)

The number of 160-gal canisters/yr is taken from Tables 7.6 or 7.7. The lb/canister is obtained by taking the weight per waste type per year from Tables 7.6 or 7.7, dividing it by the number of canisters/yr and adding to this

TABLE D.11. Disposal Costs for TRUW and HLW Based on 70,000 MTU Reprocessed[a]

Containter Size	Total Cost, $M						
	Option 1	Option 2	Option 3	Option 4	Subop-tion 5a	Subop-tion 5b	Option 6
CH, 55 gal	99	0	108	0	0	0	71
CH, 80 gal	205	0	0	0	0	0	0
CH, 160 gal	0	119	0	56	63	63	6
CH, 600 gal	5	0	0	0	0	0	0
RH, 55 gal	325	109	392	0	82	82	108
RH, 80 gal	147	0	0	0	0	0	0
RH, 160 gal	0	1226	0	535	43	43	445
RH, 600 gal	1448	0	1348	0	0	0	0
HLW, 200 L	2639	2786	2775	3013	3206	3164	2970
Total	4867	4240	4622	3603	3394	3352	3601

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

TABLE D.12. Parameters for Disposal for LLW from Option 5 Based on 1,500 MTU Reprocessed waste/yr[a]

Variable	Hulls	Hardware	Failed Equipment	Filters	Fluorinator Solids	GPT-SAC Waste
No. containers/yr	503.3	154.6	16.7	35.8	34.0	130.2
lb/canister	2,580	2,150	2,905	1,584	2,958	1,076
ft^3/yr	10,760	3,310	357	766	727	2,785
Radiation, R/hr	<100	20,000	<0.05	<0.05	0.4	<0.05
Ci/shipment	3,600	27,000	<5	<5	38	<5
No. shipments	71.7	154.6	0.7	1.5	4.8	5.57

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

quantity the 160-gal canister tare weight of 950 lb. The volume of LLW disposed per year (ft^3/yr) is based on the external volume of a 160-gal canister (21.4 ft^3).

The dose rate of decontaminated hulls was estimated from the contained quantity of ^{60}Co. It was determined that there are approximately 2E-5 Ci of ^{60}Co per g of hulls. There are 797,700 g of decontaminated hulls in a 160-gal canister, or 16 Ci of ^{60}Co. This was estimated by the authors to give a surface dose rate of 75 to 100 R/hr.

For the curie content of the hulls, it was assumed that after decontamination, the predominant radionuclides remaining would be ^{3}H, ^{14}C, ^{93}Zr and ^{93m}Nb, and that the quantities of these radionuclides would not change significantly due to decontamination. Darr (1983) specifies that there are about 239,000 Ci of these radionuclides per year in the hulls, which is equivalent to about 470 Ci per 160-gal canister of decontaminated hulls.

It is assumed that decontamination of the fuel hardware has a negligible impact on reducing its surface dose rate. In Darr (1983), a 600-gal canister of hulls and hardware with a surface dose rate of 4,600 R/hr contains 620 kg of hardware. It is estimated that 76% of this dose rate results from the ^{60}Co contained in the hardware and 24% results from ^{137}Cs, which is removed during decontamination. Therefore the surface dose rate due to the hardware is estimated to be 76% of 4,600 R/hr, or 3,500 R/hr. There is twice as much weight of low-level hardware in a 160-gal container, and the 160-gal container is about

3-1/2 times smaller. Therefore it is estimated that the surface dose rate of the low-level hulls canister is 7 times greater than 3,500 R/hr, or is about 20,000 R/hr.

For the curie content of the hardware, it was assumed that the ^{55}Fe, ^{60}Co, and ^{63}Ni are all in the hardware and that the quantity of these radionuclides remains unchanged after decontamination. Darr (1983) specifies that there are 42,000,000 Ci/yr of these radionuclides, which result in 27,000 Ci per 160-gal canister.

The decontaminable failed equipment, filters, and GPT-SAC waste can be decontaminated such that the packaged surface dose rate is less than 0.05 R/hr. It is estimated that a 160-gal canister of failed equipment, filters, and GPT-SAC waste as LLW would have a curie content of about 0.2 Ci. This estimate was obtained by setting up a ratio between dose rates and curie content given in Darr (1983).

The report DOE/LLW-6Td (EG&G, Inc. 1983) specifies that shielded shipments (hulls and fluorinator solids) contain about 150 ft^3 of LLW, and shipments of waste requiring no shielding contain about 500 ft^3 of LLW. The hardware is shipped in a commercial hulls cask and is limited to 1 canister/cask and 1 cask/shipment (McKee et al. 1984).

It is assumed for Option 5 that the TRU fluorinator solids are mixed with the non-TRU fluorinator solids to form a LLW and that the final surface dose rate is the weighted average based on initial drum volume of all the drums of fluorinator solids blended. The final surface dose rate of the blended fluorinator solids is estimated to be 0.4 R/hr. It was assumed that an estimate of the curie content of the fluorinator solids can be obtained by taking a weighted average based on weight for all the fluorinator solids in stream 41 that are blended together. This results in a content of 38 Ci/shipment.

Table D.13 gives the unit costs for disposing of the LLW by the different categories of the cost schedule in Appendix E.

TABLE D.13. Unit Cost for LLW Disposal by Cost Category

Category	Hulls	Hardware	Equipment	Filters	Solids	GPT-SAC Waste
Disposal, $/ft^3	14.50	14.50	14.50	14.50	14.50	14.50
Radiation, $/ft^3	70	2,100	0	0	0	0
Weight, $/container	250	250	250	250	250	250
Curies, $/shipment	6,000	17,600	500	500	1,500	500
Perpetuity, $/ft^3	4.75	4.75	4.75	4.75	4.75	4.75
SC LLW tax, $/ft$^{3(a)}$	4.00	4.00	4.00	4.00	4.00	4.00
Cask, $/shipment	500	500	0	0	500	0

(a) South Carolina LLW tax.

The disposal costs based on radiation level and curie content for the hardware shipments were extrapolated from the rates given on the rate schedule in Appendix E because the hardware has a high radiation level and curie content. It was assumed that the LLW facility will accept these shipments. A least squares fit of the natural log of the surface dose rate (and curie content) from the rate schedule in Appendix E versus the associated cost was performed. Plotting these points verified that the cost per shipment increases exponentially with surface dose rate (and curie content). The disposal costs of the hardware shipments were approximated by extrapolating these points to the surface dose rate and curie content associated with the decontaminated hardware.

Table D.14 gives the disposal costs per year for the LLW from Option 5 by cost category. Also included are the total costs based on 1,500 MTU and 70,000 MTU.

Some LLW is generated in Option 6 from cementation of the fluorinator solids. The disposal parameters for the fluorinator solids are:

No. of 160 gal containers = 94.6

Weight, lb/container = 734 + 950 = 1,700

Volume, ft^3/yr = 1,984

Radiation, R/hr = 1/2(initial surface dose) = 1/2(0.873 R/hr) = 0.44

TABLE D.14. Disposal Costs for LLW from Option 5[a]

Category	Cost, $M/yr						Total, $/M	
	Hulls	Hardware	Failed Equipment	Filters	Fluorinator Solids	GPT-SAC Waste	1,500 MTU	70,000 MTU
Disposal	0.156	0.048	0.005	0.011	0.011	0.040	0.27	12.6
Radiation	0.753	6.951	0	0	0	0	7.70	359.5
Weight	0.126	0.039	0.004	0.009	0.009	0.033	0.22	10.3
Curies	0.430	2.721	0.0004	0.0007	0.007	0.003	3.16	147.6
Perpetuity	0.051	0.016	0.002	0.004	0.003	0.013	0.09	4.2
SC LLW tax[b]	0.043	0.013	0.001	0.003	0.003	0.011	0.07	3.5
Cask	0.036	0.077	0	0	0.002	0	0.12	5.4
Total	1.595	9.865	0.012	0.028	0.035	0.100	11.63	543.1

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

$$\text{Ci/shipment} = (400\ \text{Ci}/15{,}136\ \text{gal})(1{,}122\ \text{gal}/150\ \text{ft}^3)(150\ \text{ft}^3/\text{shipment})$$
$$= 30$$

No. shipments = 13.0

The disposal costs for the cemented LLW from Option 6 are listed in Table D.15.

TABLE D.15. Disposal Costs for LLW from Option 6[a]

Category	Cost ($) Based on 1,500 MTU Reprocessed
Disposal	2,000
Radiation	0
Weight	23,650
Curies	19,500
Perpetuity	9,400
SC LLW tax[b]	8,000
Cask	6,500
Total based on 1,500 MTU reprocessed	69,050
Total based on 70,000 MTU reprocessed	3,200,000

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

D.4 REFERENCES

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

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

EG&G Idaho. 1983. Directions in Low-Level Radioactive Waste Management, An Analysis of Low-Level Waste Disposal Facility and Transportation Costs. DOE/LLW-6Td, Idaho Falls, Idaho.

McKee, R. W., L. L. Clark, P. M. Daling, J. F. Nesbitt, and J. L. Swanson. 1984. "Economic Analysis of Waste Management System Alternatives for Reprocessing Wastes." Waste Management 1984, pp. 383-393. University of Arizona, Tucson.

McNair, G. W. et al. 1984. Truck and Rail Charges for Shipping Spent Fuel and Nuclear Waste. PNL-4064, Pacific Northwest Laboratory, Richland, Washington.

Rasmussen, D. E. 1982. Comparison of Cask and Drywell Storage Concepts for a Monitored Retrievable Storage/Interim Storage System. PNL-4450, Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy. 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028 in 5 volumes, U.S. DOE, Washington, D.C.

Wilmot, E. L. et al. 1983. A Preliminary Analysis of the Cost and Risk of Transporting Nuclear Waste to Potential Candidate Commercial Repository Sites. SAND83-0867, Sandia National Laboratories, Albuquerque, New Mexico.

APPENDIX E

RATE SCHEDULE FOR THE BARNWELL LOW-LEVEL RADIOACTIVE WASTE DISPOSAL FACILITY

APPENDIX E

RATE SCHEDULE FOR THE BARNWELL LOW-LEVEL RADIOACTIVE WASTE DISPOSAL FACILITY[a]

All radwaste material shall comply with Department of Transportation packaging specifications in accordance with Title 49 and Title 10 of the Code of Federal Regulations, CNSI's Nuclear Regulatory Commission and South Carolina Radioactive Material Licenses, CNSI's Barnwell Site Disposal Criteria, and amendments thereto.

1. DISPOSAL CHARGES: (Not including surcharges)

   A. $14.50 per cubic foot, but not less than $300.00 per shipment

2. SURCHARGES:

   A. Radiation Surcharges - steel drums, boxes, and liners:

Maximum Radiation Level at Package Surface (R/hr)	Radiation Surcharge ($ per cubic foot)
0 - 0.050	No surcharge
0.051 - 0.100	$ 5.00
0.101 - 0.250	8.00
0.251 - 0.500	10.00
0.501 - 1	13.00
1.001 - 5	15.00
5.001 - 10	20.00
10.001 - 25	30.00
25.001 - 50	40.00
50.001 - 75	50.00
75.001 - 100	70.00
100.001 - 125	80.00
125.001 - 250	100.00
250.001 - 500	200.00
500.001 - 1000	300.00
1,000.001 - 5000	400.00
Greater than 5000 R/hr	By Special Request

(a) This rate schedule, from Chem-Nuclear Systems, Inc., was effective January 1, 1984, and was used to calculate the LLW disposal costs in Appendix D.

B. Weight Surcharges

Weight of Container			Surcharge Per Container
0	-	1,000 lb	No Surcharge
1,000	-	5,000 lb	$ 250.000
5,000	-	10,000 lb	500.00
10,000	-	20,000 lb	750.00
20,000	-	30,000 lb	1,000.00
30,000	-	40,000 lb	1,500.00
40,000	-	50,000 lb	2,000.00
greater than		50,000 lb	By Special Request

C. Curie Surcharges:

Curie Content			Surcharge Per Shipment
0	-	1	No Surcharge
1.001	-	5	$ 500.00
5.001	-	15	750.00
15.001	-	25	1,000.00
25.001	-	50	1,500.00
50.001	-	75	2,000.00
75.001	-	100	2,500.00
100.001	-	150	3,000.00
150.001	-	250	4,000.00
250.001	-	500	5,000.00
500.001	-	1,000	6,000.00
1,000.001	-	5,000	8,000.00
Greater than		5,000	By Special Request

D. Biological Tissue Surcharge $ 1.00 per cubic foot

E. Special handling surcharge: Applicable on unusually large or bulky containers

3. CASK HANDLING FEE $500.00 per cask, minimum

4. TAXES AND SPECIAL FUNDS

A. Perpetuity Escrow Fund $2.25 per cubic foot
2.50 per cubic foot effective April 5, 1984

B. S.C. Low Level Radioactive Waste Disposal Tax $4.00 per cubic foot

C. Barnwell County Business License Tax:
A 2.4% Barnwell County Business License Tax shall be added to the total of all disposal fees.

NOTE: Fees noted in Item 34, A, B, and C shall be stated separately on all disposal invoices.

5. MISCELLANEOUS:

A. Transport vehicles which are provided with additional shielding features may be subject to a minimum handling fee of $150.00 per use. Such a fee covers additional handling and labor required for special equipment set up and temporary shield removal.

B. Decontamination services (if required): $50.00 per man-hour plus supplies at current CNSI rate.

C. Customers may be charged for all special services as described in the Barnwell Site Disposal Criteria.

D. Terms of payment are NET 30 DAYS upon presentation of invoices. A service charge per month of the maximum rate permitted by law may be levied on accounts paid after thirty (30) days.

E. Company purchase orders or a written letter of authorization in form and substance acceptable to CNSI shall be received before receipt of radioactive waste material at the Barnwell Disposal Site and shall refer to CNSI's Radioactive Material Licenses, the Barnwell Site Disposal Criteria, and subsequent changes thereto.

F. All shipments shall receive a CNSI allocation number and conform to the Prior Notification Plan. Additional information may be obtained at (803) 259-3577 or (803) 259-3578.

G. This Rate Schedule is subject to change and does not constitute an offer of contract which is capable of being accepted by any party.

H. A charge of $5,000.00 is applicable to all shipments which require special site set-up for waste disposal.

APPENDIX F

ADDITIONAL INFORMATION ON THE EVALUATION OF PROCESSING CHARACTERISTICS

APPENDIX F

ADDITIONAL INFORMATION ON THE EVALUATION OF PROCESSING CHARACTERISTICS

This appendix provides additional information on the processing characteristics evaluation of the treatment options as presented in Section 9. Tables F.1 through F.4 were developed by the authors after considerable discussion of background relating to the factors and qualitative ratings.

Table F.1 gives the results of evaluations relating to operational safety. Some abbreviated explanations of the ratings are provided below.

Option 1 - no treatment - has low accident potential for most operations, since there is no extra handling of the wastes or equipment. However, the waste does contain combustibles and fuel cladding hull fines that may be pyrophoric, and thus the no treatment option does involve some risk of fire.

Option 2 - minimum treatment - has a potential for fire or explosion because of the potential for generating hull fines and for initiating a pyrophoric chemical reaction during compaction. Since the mechanical compaction presses would be operated remotely, the compaction process would present a low hazard to personnel. The contact handled shredder, however, would provide some mechanical hazard to operating personnel.

Option 3 - minimum number of processes and products - involves incorporating the hulls into cement, thus reducing the fire hazard. But this option would also involve some mechanical operations in the proximity of operating personnel for treatment of other waste.

Option 4 - maximum volume reduction without decontamination - uses several operations involving high temperatures, the transfer of molten material, and incineration, all of which have an associated fire hazard and radiochemical volatility potential. Shredding and other mechanical handling operations would expose operating

TABLE F.1. Qualitative Comparison of Relative Operational Safety Among the Six TRUW Treatment Options[a]

Treatment Options	Chemical Hazard	Fire or Explosion Potential	Mechanical Hazard	Electrical Hazard	Radiochemical Release	Overall Operational Safety
1. No treatment	Very good	Good	Very good	Very good	Very good	Very good
2. Minimum treatment	Very good	Moderate	Good	Very good	Very good	Good
3. Minimum number of processes	Good	Good	Good	Very good	Very good	Good
4. Maximum volume reduction without decon.	Good	Fair	Fair	Fair	Fair[b]	Fair
5. Maximum volume reduction with decon.	Moderate	Fair	Fair	Moderate	Moderate[b]	Moderate
6. Noncombustible waste forms	Good	Moderate	Fair	Moderate	Fair[b]	Moderate

(a) Ratings for each hazard category are relative even though all the hazards are believed to be acceptable with conventional design and operating practices. Ratings range from very good (most favorable) to fair (least favorable). No attempt is made to determine which hazard category is the most important.
(b) Off-gas systems are available to control radiochemical releases to safe levels.

personnel to some of these hazards. The melting and shredding equipment would use high electrical current usage and would therefore increase this hazard.

Option 5 - maximum volume reduction with decontamination - causes some concern about the handling of liquid nitrogen and fuel cladding hulls, since the decontamination operation would generate a fine zirconium powder as material is removed from the hull surface. Some of this fine material would remain as a metal powder and may have pyrophoric tendencies during lag storage and later process operations. Since the melting of the metallic wastes would be avoided, there would be less opportunity for volatilizing the radionuclides. Decontamination residues would still be immobilized, but the quantity

of material requiring treatment for repository disposal is much less for Option 5 than for the other options. While electrical power requirements will likely be less for Option 5 than for the options using melting, the operations will still likely use significant electrical power.

Option 6 - noncombustible waste forms - is similar in part to Option 4 (maximum volume reduction without decontamination), and it therefore has similar safety considerations. However, Option 6 has lower fire and explosion potential because fewer high-temperature processes are utilized and no fuel cladding hull fines are produced. Option 6 would also use less lower electrical power usage than Option 4 and would therefore have lower potential electrical hazards. Since cement is one of the waste forms, there would be some potential for radiolytic gas generation.

The complexity of the treatment processes is compared qualitatively by the number of processes and the number of steps in the process. In general, the more complex the treatment, the greater the cost of the process equipment and the facility space, the greater the likelihood of process upsets and equipment failure, and therefore the lower the operating efficiency of the process as a whole. For this assessment, two measures of process complexity were determined and are shown in Table F.2. The two measures consist of the number of major process units required and the number of major flowsheet steps shown in Section 7 for each of the respective treatment strategies. In the last column in Table F.2, the process simplicity (i.e., inverse of complexity) is derived and is given in Table 9.2.

The status of technology in this study was qualitatively classified by the stage of development of the hardware: conceptual, laboratory or bench scale, nonradioactive pilot or engineering scale, or radioactively operational. This distinction, based on the knowledge of the authors and on review of the literature, is shown in Table F.3. The judgments are based primarily on the use of the process for the specific wastes of interest in this study and the state of development of the equipment; previous applications of the technology to waste treatments are also recognized. In the last column of Table F.3, the overall qualitative rating is derived and is given in Table 9.2.

TABLE F.2. Qualitative Comparison of Relative Process Simplicity for the Six TRUW Treatment Options

Treatment Option	Process Units[a]	Number of Steps in Flowsheet[b]	Overall Simplicity[c]
1. No treatment	None	1	Very good
2. Minimum treatment	RH compactor RH size reduction CH size reduction	7	Good
3. Minimum number of processes and products	CH shredder RH shredder RH in-drum cement mixer RH external cement mixer	9	Good
4. Maximum volume reduction without decontamination	RH melter for metals and ceramics RH shredder RH incinerator RH low-temperature, hot press	12	Moderate
5. Maximum volume reduction with decontamination	Hull cryogenic cracker RH centrifugal barrel finisher RH compactor RH shredder RH blender RH vibratory finisher RH incinerator LLW cement mixer[d] CH precipitator RH high-temperature hot press (Option 5B only)	15	Fair
6. Noncombustible waste forms	RH melter for metals CH shredder RH shredder RH incinerator RH in-drum cement mixer	11	Moderate

(a) An effective assay system is required for each option. Sorting is not shown as a process unit but will be required for several options.
(b) Taken from Section 7.
(c) The relative ratings are from very good (the most favorable) to fair (the least favorable in the group).
(d) May already be available in the existing LLW treatment facility.

A qualitative comparison was made of the flexibility of the processes to handle a variety of waste characteristics. This was done by first qualitatively evaluating the flexibility of each process step, as shown in the Column 3 of Table F.4. In the last column of Table F.4, the overall qualitative rating is derived and is given in Table 9.2.

TABLE F.3. Qualitative Comparison of the Status of Technology for the Six TRUW Treatment Options

Treatment Option	Process[a]	Status of Technology	Overall Status[b]
1. No treatment	None	Operational	Very good
2. Minimum treatment	RH compactor	Operational	Very good
	CH size reduction	Operational	
	RH size reduction	Cold pilot scale	
3. Minimum number of processes and products	CH shredder	Operational	Very good
	RH shredder	Cold pilot scale	
	RH in-drum cement mixer	Operational	
	RH external cement mixer	Operational	
4. Maximum volume reduction without decontamination	RH melter	Cold pilot scale	Moderate
	RH shredder	Cold pilot scale	
	RH incinerator	Contact operational	
	RH low-temperature hot press	Conceptual	
5. Maximum volume reduction with decontamination	Hull cryogenic cracker	Conceptual	Fair
	RH centrifugal barrel finisher	Bench scale	
	RH compactor	Operational	
	RH shredder	Contact operational	
	RH blender	Operational	
	RH vibratory finisher	Cold pilot scale	
	RH incinerator	Contact operational	
	LLW cement mixer[c]	Operational	
	Precipitator	Conceptual	
	RH high-temperature hot press (Option 5B only)	Laboratory scale	
6. Noncombustible waste forms	RH melter for metals	Cold pilot scale	Good
	CH shredder	Operational	
	RH shredder	Cold pilot scale	
	RH incinerator	Contact operational	
	RH in-drum cement mixer	Operational	

(a) An effective assay system is required for each of the options.
(b) The relative ratings are from very good (the most favorable) to fair (the least favorable in the group).
(c) May already be available in the existing LLW treatment facility.

TABLE F.4. Qualitative Comparison of Process Flexibility for the Six TRUW Treatment Options

Treatment Option	Process Units[a]	Flexibility of Process Steps[a]	Overall Process Flexibility[b]
1. No treatment	None	Very good	Very good
2. Minimum treatment	RH compactor	Good	
	CH size reduction	Very good	Good
	RH size reduction	Good	
3. Minimum number of processes and products	CH shredder	Good	
	RH shredder	Good	
	RH in-drum cement mixer	Very good	Good
	RH external cement mixer	Very good	
4. Maximum volume reduction without decontamination	RH melter	Good	
	RH shredder	Good	Fair
	RH incinerator	Fair	
	RH low-temperature hot press	Fair	
5. Maximum volume reduction with decontamination	Hull cracker	Fair	
	RH centrifugal barrel finisher	Fair	
	RH compactor	Good	
	RH shredder	Good	Fair
	RH blender	Good	
	RH vibratory finisher	Fair	
	RH incinerator	Fair	
	LLW cement mixer[c]	Very good	
	Precipitator	Good	
	RH high-temperature hot press (Option 5B only)	Fair	
6. Noncombustible waste forms	RH metallic melter	Good	
	CH shredder	Good	Good
	RH shredder	Good	
	RH incinerator	Fair	
	RH in-drum cement mixer	Very good	

(a) An effective assay system is required for each option.
(b) The relative ratings are from very good (the most favorable) to fair (the least favorable in the group).
(c) May already be available in the existing LLW treatment facility.

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