**AQUEOUS NITRATE WASTE TREATMENT:
TECHNOLOGY COMPARISON, COST/BENEFIT,
AND MARKET ANALYSIS**

**U.S. DEPARTMENT OF ENERGY
OAK RIDGE OPERATIONS**

Prepared for

OFFICE OF TECHNOLOGY DEVELOPMENT

By

KAPLINE ENTERPRISES, INC.

January 1994

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CHAPTER 1. INTRODUCTION

PURPOSE OF PROJECT

The purpose of this analysis is to provide information necessary for the Department of Energy (DOE) to evaluate the practical utility of the Nitrate to Ammonia and Ceramic or Glass (NAC/NAG/NAX) process, which is under development in the Oak Ridge National Laboratory. The NAC/NAG/NAX process can convert aqueous radioactive nitrate-laden waste to a glass, ceramic, or grout solid waste form.

STATEMENT OF WORK

The tasks that DOE requested KapLine Enterprises, Inc. (KEI) to perform include, but are not limited to, the following:

1. Identify current commercial technologies to meet hazardous and radiological waste disposal requirements. The technologies may be thermal or non-thermal but must be all inclusive (i.e., must convert a radionuclide-containing nitrate waste with a pH around 12 to a stable form that can be disposed at permitted facilities).
2. Evaluate and compare DOE-sponsored vitrification, grouting, and minimum additive waste stabilization projects for life-cycle costs.
3. Compare the technologies above with respect to material costs, capital equipment costs, operating costs, and operating efficiencies. For the NAC/NAG/NAX process, assume aluminum reactant is government furnished and ammonia gas may be marketed.
4. Compare the identified technologies with respect to frequency of use within DOE for environmental management applications with appropriate rationale for use.
5. Assess the potential size of the DOE market for the NAC/NAG/NAX process based on technology limitations.
6. Assess comparable technologies' off-gas issues with uncertainties bounded.
7. To the extent possible, compare with international technologies, including life-cycle estimates.

PROPOSED METHODOLOGY

In gathering the requested information, KEI reviewed the secondary literature and conducted telephone and local, in-person interviews of DOE, EPA, and private-sector experts.

SCOPE AND FORMAT

The scope of this research is primarily the U.S. DOE market for the treatment of aqueous nitrate low-level waste. In addition to meeting the objectives of the Statement of Work, KEI intends for this report to be a comprehensive reference document on the subject of aqueous nitrate waste treatment technologies as well as other pertinent issues such as solid-waste disposal. The following topics are addressed in this study:

- Problem definition and the DOE market (Chapter 3).
- Technical discussion of nitrate-treatment technologies including chemical processes (reduction, biological, NAC/NAG/NAX), thermal conversion, and solidification/stabilization (Chapter 4).
- Treatment issues such as feed pretreatments, off-gas treatment, reclamation/reuse, and final waste forms (Chapter 5).
- Economic analysis (Chapter 6, Appendix 3).
- Estimating principles (Appendix 3).
- Previous cost estimates (Appendix 4).
- Crosswalk Database search results (Appendix 5).
- Important contacts (Appendices 6).
- List of references (Appendix 7).

DISCLAIMER

KEI performs work on a best-effort basis only and assumes no liability for the inability to obtain information. In particular, information regarding international applications and markets is extremely difficult to obtain and KEI expends very limited resources searching for this information.

Although KEI intends the work to be as reliable as possible and professional in nature, KEI assumes no liability for the information that is provided or for its use. KEI assumes no liability for loss or damage that occurs as a result of reliance on this information or any material developed from it. The documents that result from this research are not legal or accounting documents and some of the information contained therein may be speculative or may be based on KEI's best engineering judgment. However, KEI makes every effort to document assumptions that are made when reporting speculative or best-judgment information. Any reference to a trade name does not indicate endorsement of a particular product.

CHAPTER 2. EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) has determined that nitrate in ground water can pose a serious threat to the health of the public. As a result, the agency has set the nitrate concentration limit for discharge at 44 ppm (44 mg/l) nitrate (NO_3) or 10 ppm monatomic nitrogen (N), and 1 ppm as nitrite (NO_2).

Nitrogen oxide emissions in off-gases are also regulated by the EPA as well as state and local governments. Southern California currently has the most stringent regulations regarding NO_x emissions. As a result of these regulations, thermal processes that result in their formation must be equipped with pollution-control systems to prevent their release.

DOE PROBLEM DEFINITION OVERVIEW

Sodium nitrate-based wastes are common to many DOE facilities throughout the United States. The nuclear industry, both commercial and defense related, has historically used large quantities of nitric acid in the processing of spent reactor fuels and in actinide recovery and purification processes. This usage generates large quantities of nitrate wastes, which are either stored or, in some cases, released to the environment.

In the past, nitrate wastes were not a matter of much concern. The amount of nitrate generated at most U.S. facilities, many of which were commercial and defense nuclear sites, was considered low enough to be handled by the dilution-and-discharge method. However, lower permissible limits on nitrates in plant discharge water may require some nuclear facilities to process their nitrate waste in a different manner.

This is due to increasing regulation by the EPA, Nuclear Regulatory Commission (NRC), and legislation such as the Resource Conservation and Recovery Act (RCRA). The shipment and burial of dry powdered nitrate salts have been ruled out, so new methods for final disposal of nitrate wastes are needed. The high solubility of virtually all nitrate compounds and the low limit for nitrate (45 mg/l) in plant effluents and ground water make the presence of nitrate in disposed waste highly problematic and provide a strong incentive to destroy the nitrate prior to either storage or disposal.

The NRC-proposed Rule 10 CFR 61 governs the disposal of low-level radioactive wastes in "near surface" or shallow land burial. Although nitrates were not specifically excluded as a waste form in this proposed regulation, it is clear they do not meet the criteria established in the regulation for a Class B stable waste. In addition, they do not meet the criteria established in the National Primary Drinking Water Quality Criteria (DWQC) Standard (40 CFR 141), which is referenced as a portion of this regulation.

Chemical process effluents, which also include ground water seepage from shallow burial sites, must now meet the more restrictive DWQC Standards. Variances are still in effect at DOE sites, but these may be revoked in the future, and commercial operations must adhere to present EPA requirements. As a result, DOE is evaluating and developing new ways of treating nitrate-based wastes, particularly those technologies that destroy the nitrate.

DOE MARKET OVERVIEW

Summary Table 1 presents the quantity of nitrate/nitrite waste being stored and generated at the defense facilities. Note, however, that because the table is from a 1986 report, the current numbers are probably somewhat higher.

SUMMARY TABLE 1
SUMMARY OF NITRATE STORAGE AND GENERATION AT
DEFENSE FACILITIES

Site	Type	Stored Nitrate, kg	Generation Rate	Comments
Feed Materials Production Center	Effluent	--	2,200,000 ^a	Biodenitrification planned
Hanford-Rockwell	Effluent	--	1,100,000 ^a	Discharged to ponds, cribs, etc.
Hanford-Rockwell	LLW, HLW, TRU	145,000,000 ^b	1,180,000 ^b	Stored in tanks
Hanford-United Nuclear	LLW	980,000 ^a	2,020,000 ^a	Discharged to solar ponds
Idaho Chemical Processing Plant	HLW	1,460,000 ^a	(24,000) ^a reduction	Liquid in tanks, NO _x released
Idaho Chemical Processing Plant	HLW	92,800 ^a	13,000 ^a	Calcine in bin sets
Idaho-Radioactive Waste Manage- ment Complex	LLW or TRU	11,300,000 ^b	----	Buried or stored
Los Alamos National Laboratory	Effluents	----	70,800 ^a	Discharged to canyon
Lawrence Livermore National Lab.	LLW	----	<200 ^a	Cemented, shipped to NTS
Mound Facility	LLW	----	1,500 ^c	Cemented, shipped to NTS
Nevada Test Site	LLW	10,400,000 ^b	----	Receives RFP salts, FY78-FY85
Oak Ridge Y-12 Plant	Effluents	----	664,000 ^a	Acid recycle biodenitrification
Rocky Flats Plant	LLW	----	930,000 to 2,050,000 ^b	Salts/salterete shipped to NTS
Rocky Flats Plant	LLW	1,450,000 ^b	----	Solar ponds being decommissioned
Savannah River Plant	HLW	82,900,000 ^b	1,480,000 to 2,960,000 ^b	Grouting facility planned
TNS-Aerojet	LLW	82,900,000 ^b	38,000 ^a	Discharged to creek
West Valley Pilot Project	HLW	557,000 ^a	----	Basic waste
West Valley Pilot Project	HLW	73,300 ^b	----	Acidic waste
TOTALS		254,000,000	7,500,000 to 11,200,000	

^a Based on nitrate ion. ^b Based on nitrate compounds. ^c As cemented Fe(OH)₃ sludge

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP- 3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

TECHNOLOGIES AND FREQUENCY OF USE

According to *Evaluation of Nitrate Destruction Methods* (DOE/MWIP-10, March 1993), three destruction processes have been used to treat high nitrate-concentration wastes at full-scale facilities: biological denitrification, calcining, and chemical reduction. Two full-scale vitrification plants are currently under construction, one at Savannah River and the other at Hanford. Both of these facilities are for processing high-level radioactive wastes.

Grouting, which is also included in KEI's analysis, does not destroy or immobilize nitrates. As a result, the grouted material must be encased in vaults to prevent ion (e.g., sodium) migration. Other well-established non-destructive nitrate-treatment technologies are: ion exchange, reverse osmosis, and electrodialysis reversal (nitrate only). These are considered by the EPA to be Best Available Technologies (BAT) for nitrate removal from drinking water. The BATs, however, simply create a secondary waste stream that must be treated and are not the ultimate solution to the problem.

ECONOMIC ANALYSIS

The economic analysis presented in this report is KEI's adaptation and expansion of work that has been previously funded by the DOE. In particular, KEI based the performance scenario used in the analysis and the assumed final waste outputs on a mass balance provided by the NAC/NAG/NAX researchers at Oak Ridge National Laboratory (ORNL). KEI also relied on assumptions made in a 1992 NAC cost estimate done by Martin Marietta cost estimator, David Brashears (Central Engineering Services). The costs for vitrification and grouting were extrapolated from cost data presented in the report, *Waste Management Facilities Cost Information (WMFCI) for Mixed Low-Level Waste* (EGG-WM-10962, March 1994).

Note that KEI developed a computer model based on the data presented in the WMFCI document in order to easily compare costs that result from different assumptions and to easily expand on this and other work in future projects.

ASSUMPTIONS

Throughout this report, KEI assumed a 20-year processing period, around-the-clock operations 365 days/year with 60% availability (i.e., 5,256 hr/yr). The assumed Hanford-scale feed throughput is 7,061 kg/hr, which includes a nitrate/nitrate feed rate of 1,084 kg/hr and a sodium feed rate of 563 kg/hr. The total volume treated is assumed to be 600 million liters of waste, which contains 2.6 billion gram-moles of sodium (4.3 M). KEI also assumed that the cesium has been removed and that the final glass product will have <100 nCi alpha/g.

ANALYSIS VARIABLES

KEI's cost analysis can be broken down into two segments: 1) grouting and vitrification and 2) NAC/NAG/NAX. The analyses of the grouting and vitrification facility costs are based on WMFCI estimates of the facility construction and building costs and extrapolations of their data. However, these costs for the NAC/NAG/NAX process were not determined by the WMFCI team. The costs used by KEI came in part from the Martin Marietta Energy Systems (MMES) cost analysis while the remainder were developed by KEI, which made

every attempt to make the cost components used in the NAC/NAG/NAX analysis consistent with those used in the vitrification and grouting analyses. This is extremely important in making direct comparisons of the numbers.

Note that there are several components to the KEI life-cycle cost for each of the treatment technologies. They can be categorized as EG&G life-cycle cost and others not included by the EG&G methodology. These other components include transportation and disposal of the final waste product and additional off-gas treatment for vitrification and NAC/NAG/NAX. Disposal variables are on-site (engineered or shallow land) versus off-site (Envirocare). Note that transportation costs for off-site disposal are the same for non-alpha and alpha as long as any radioactivity is present.

The cost analysis considers the effect of vitrification off-gas treatment on life-cycle costs assuming a high (\$6,000/ton NO_x) and a low value (\$1,000/ton NO_x). Note, however, that these costs assume the off-gas is not radioactive. A contaminated off-gas would probably require an even more expensive system.

NAC/NAG/NAX variables are final waste form, the cost of aluminum, and the disposition of the ammonia off-gas. Final waste form options are to calcine the reaction product (NAC) or convert it to a glass waste form through vitrification (NAG). Another option is to solidify the uncalcined reaction product by reaction with a chemical such as lime (NAX). KEI assumed that the aluminum consumed in the process is government supplied and, therefore, applied a credit for the cost of aluminum. KEI applied no credit for ammonia sales because of the unlikelihood of such sales due to poor process economics.

RESULTS OVERVIEW

Summary Figure 1 presents KEI life-cycle cost comparisons assuming off-site disposal at Envirocare for the final waste generated by the NAC/NAG/NAX, vitrification, and grouting processes for treating alpha (>10 nCi/g TRU) nitrate waste. These are presented because KEI assumes that Envirocare disposal is the most likely option, in particular because it is the least expensive. However, the analysis also evaluated on-site disposal options (e.g., shallow land burial and engineered disposal).

The EG&G life-cycle cost is comprised of facility construction, operating and maintenance, other (e.g., demonstration, studies, operations budget funded activities, decommissioning and decontamination, and credits), while the KEI life-cycle cost also includes additional off-gas treatment (NO_x for vitrification and ammonia for NAC/NAG/NAX), and disposal (on-site engineered or shallow land and off-site shallow land). Summary Table 2 presents an overview of these data while Summary Figure 1 represents it graphically.

SUMMARY TABLE 2
KEI LIFE-CYCLE COST COMPARISON: NAC, NAG, NAX,
VITRIFICATION, AND GROUTING (ALPHA)

	VITRIFICATION	GROUTING	NAC	
			LOW	HIGH
EG&G life-cycle	5,368,837	566,898	738,996	1,148,973
Studies & tests	108,883	--	54,192	54,192
Demonstration	163,413	--	81,707	81,707
Facility construction	1,044,069	182,785	92,229	445,412
Operations funded	698,608	24,160	29,018	38,731
budget activities				
Operating & maint.	3,260,255	346,400	481,500	481,500
D&D	94,109	13,553	6,750	53,831
Process credits	---	---	(6,400)	(6,400)
Off-gas treatment (NOx)	125,345-752,074	---	---	---
Disposal				
Off-site: Envirocare	1,162,434	1,818,600	776,472	776,472
Transportation	24,698	38,640	16,497	16,497
Disposal fee	1,137,736	1,779,960	759,975	759,975
On-site: Shallow land	1,401,155	1,846,298	1,101,264	1,101,264
On-site: Engineered	2,726,240	3,541,520	2,141,422	2,141,422
TOTAL				
Off-site: Envirocare	6,656,616-7,283,345	2,385,498	1,515,468	1,925,445
On-site: Shallow land	6,895,337-7,522,066	2,413,196	1,840,260	2,250,237
On-site: Engineered	8,220,422-8,847,151	4,108,418	2,880,418	3,290,395
	NAG		NAX	
	LOW	HIGH	LOW	HIGH
EG&G life-cycle	2,275,354	2,685,856	1,135,538	1,546,042
Studies & tests	54,192	54,192	54,192	54,192
Demonstration	81,707	81,707	81,707	81,707
Facility construction	408,098	761,792	122,486	476,182
Operations funded	100,879	110,606	48,903	58,630
budget activities				
Operating & maint.	1,630,128	1,630,128	827,900	827,900
D&D	6,750	53,831	6,750	53,831
Process credits	(6,400)	(6,400)	(6,400)	(6,400)
Off-gas treatment (NOx)	---	---	---	---
Disposal				
Off-site: Envirocare	1,162,434	1,162,434	1,631,328	1,631,328
Transportation	24,698	24,698	34,661	34,661
Disposal fee	1,137,736	1,137,736	1,596,667	1,596,667
On-site: Shallow land	1,401,155	1,401,155	1,717,078	1,717,078
On-site: Engineered	2,726,240	2,726,240	3,340,934	3,340,934
TOTAL				
Off-site: Envirocare	3,437,788	3,848,290	2,766,866	3,177,370
On-site: Shallow land	3,676,509	4,087,011	2,852,616	3,263,120
On-site: Engineered	5,001,594	5,412,096	4,476,472	4,886,976

Source: KEI

KEI LIFE-CYCLE COST

(ALPHA, OFF-SITE)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 & \$6000/TON NOx

CONCLUSIONS

The results of KET's analysis indicate that NAC offers the most economical alternative to grouting, which does not truly solve the nitrate problem—it simply defers the problem to future generations due to ion migration. Grouting also produces a large volume of waste that must be disposed. The use of vitrification does not appear to be economical compared with these NAC and grouting due to the high life-cycle cost, which mostly is due to its high operating and maintenance costs.

NAC/NAG/NAX offers the advantages of nitrate destruction (as opposed to grouting) and no NO_x generation. NAC and NAG immobilize many inorganic contaminants such as PO_4 , SO_4 , Cl, F, Cr, Al, Cs, Tc, and ^{90}Sr , and the consumption of scrap aluminum. Disadvantages of the process include the need for an off-gas system to handle ammonia, the need for safety controls due to the highly exothermic nature of the process, and potential hydrogen generation.

CHAPTER 3. PROBLEM DEFINITION AND THE DOE MARKET

The EPA has determined that nitrate in ground water can pose a serious threat to the health of the public. As a result, the agency has set the nitrate concentration limit for discharge at 44 ppm (44 mg/l) nitrate (NO_3) or 10 ppm monatomic nitrogen (N), and 1 ppm as nitrite (NO_2). Sources of information regarding EPA nitrate policy for drinking water and BATs for removing (not destroying) nitrate from water are the following: *Federal Register*, Proposed Rules, Vol. 54, No. 97, Monday, May 22, 1988, and *Federal Register*, Final Rules, Vol. 56, No. 20, Wednesday, January 30, 1991. BATs for nitrate and nitrite removal from drinking water are ion exchange, reverse osmosis, and electrodialysis reversal (nitrate only).

DOE PROBLEM DEFINITION

The nuclear industry has historically used large quantities of nitric acid in the processing of spent reactor fuels and in actinide recovery and purification processes. This usage generates large quantities of nitrate wastes, which are either stored or released to the environment.

In the past, nitrate wastes were not a matter of much concern. The amount of nitrate generated at most U.S. facilities, most of which were commercial and defense nuclear sites, was considered low enough to be handled by the dilution-and-discharge method. However, lower permissible limits on nitrates in plant discharge water may require some nuclear facilities to process their nitrate waste in a different manner.

Increasing regulation by the EPA, NRC, and legislation such as the RCRA are causing concern in the U.S. nuclear industries in regard to the treatment and disposal of nitrate wastes. The shipment and burial of dry powdered nitrate salts have been ruled out, so new methods for final disposal of nitrate wastes are needed.

The NRC-proposed Rule 10 CFR 61 governs the disposal of low-level radioactive wastes in "near surface" or shallow land burial. Although nitrates were not specifically excluded as a waste form in this proposed regulation, it is clear they do not meet the criteria established in the regulation for a Class B stable waste. In addition, they do not meet the criteria established in the National Primary Drinking Water Quality Criteria (DWQC) Standard (40 CFR 141), which is referenced as a portion of this regulation.

Chemical process effluents, which also include ground water seepage from shallow burial sites, must now meet the more restrictive DWQC Standards. Variances are still in effect at DOE sites, but these may be revoked in the future, and commercial operations must adhere to present EPA requirements. As a result, DOE is evaluating and developing new ways of treating nitrate-based wastes, particularly those technologies that destroy the nitrate by converting it to other forms.

DOE MARKET

A wide variety of nitrate-containing aqueous mixed wastes are produced and/or stored at various DOE facilities. The high solubility of virtually all nitrate compounds and the low limit for nitrate (45 mg/l) in plant effluents and ground water make the presence of nitrate in disposed waste highly problematic and provide a strong incentive to destroy the nitrate prior to either storage or disposal.

COMMERCIAL NUCLEAR-FUEL-CYCLE NITRATE WASTES

The information in this section was obtained from *Commercial and Defense Nitrate Wastes and Processing Alternatives* (DOE/TIC-4500). Wastes that are classified as low-level radioactive wastes are generated throughout the commercial nuclear fuel cycle from the initial mining of the uranium ore through to the end product, energy from a nuclear power reactor. The amount of nitrates in the waste generated by the commercial sector of the fuel cycle is quite low compared to that generated by defense activities. Since the radioactivity of this commercial waste can be reduced to near background levels, it is now treated and released at most sites. A significant decrease in the EPA allowable nitrate levels of water discharged, however, could create problems if an alternate nitrate disposal method is not available.

Operations in the commercial fuel cycle can be conveniently divided into quite distinct activities that generally take place at geographically separate facilities. These activities are mining and milling, uranium conversion, enrichment, fuel fabrication, power generation, fuel reprocessing, and waste disposal. Table 1 summarizes the nitrate wastes generated in the commercial fuel cycle activities. Table 2 lists the nitrate wastes by facility.

Mining and Milling

Mining operations for uranium ore can be considered as generating no nitrate waste. During the subsequent milling operations, the uranium is concentrated as yellow cake or U_3O_8 . Although this operation results in a large amount of liquid waste containing low levels of activity, essentially no nitric acid is used in present processes. Both mining and milling can be considered as generating no significant amounts of nitrate wastes from current operations.

Uranium Conversion— U_3O_8 to UF_6

The uranium oxide from the mills is converted to UF_6 for head-end feed to the gaseous diffusion enrichment units. Two commercial conversion plants are now in production, one using a dry, the other a wet fluorination process.

The Allied Corp. Facility at Metropolis, IL, uses the dry Hydrofluor process, in which the uranium concentrate is carried through successive reduction, hydrofluorination, and fluorination in fluidized-bed reactors. Crude uranium hexafluoride is then further purified and recovered by fractional distillation. Virtually no nitrate wastes are generated by this process.

TABLE 1
NITRATE WASTES GENERATED IN COMMERCIAL FUEL CYCLE
ACTIVITIES

ACTIVITY	LOCATION	GENERATION RATE PER YEAR	AMOUNT STORED	REMARKS
Mining and milling	All	Virtually none	None	No significant amounts of nitrate waste from current processes.
Conversion	Allied Chemical Metropolis, IL	None	None	Use dry hydrofluor process. ¹
	Kerr-McGee Sequoyah, OK	9.1×10^5 kg	None	Converted to NH_4NO_3 and used as in-plant fertilizer. ²
Enrichment (all gaseous diffusion)	Martin Marietta (K-25*), Oak Ridge, TN	Included in Oak Ridge rate.	None	Transported to Oak Ridge Y-12 for biodenitrification. ³
	Paducah, KY	8.1×10^3 kg solution	None	Transported to Oak Ridge Y-12 for further use. (Other small amounts treated and discharged.) ⁴
	Goodyear Atomic Piketon, OH	3.8×10^4 kg	None	Treated and released. ⁵
Power Generation	All	None	None	⁶

¹ Marshall Shepard, Allied Corp., Metropolis, IL, G.F. Jaskot, personal communication.

² William Shelly, Kerr-McGee Nuclear Corp., Sequoyah, OK, G.F. Jaskot, personal communication.

³ F.E. Clark, H.C. Francke, et al., "Denitrification of Acid Wastes from Uranium Purification Processes," Report Y-1990, Union Carbide Corp., ORNL, 1975.

⁴ C.K. Conrad, Union Carbide, Paducah, KY, A.J. Johnson, personal communication.

⁵ M.E. Holland, "Biodenitrification of Gaseous Diffusion Plant Aqueous Wastes: Stirred-Bed Reactor," GAT-2002 Goodyear Atomic Corp., Piketon, OH, 1980.

⁶ Light-water reactors, both the BWR and PWR types, can be classified as generating no significant amounts of nitrate wastes.

* Shut down in late 1980s.

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

TABLE 2
NITRATE WASTE FROM COMMERCIAL FUEL CYCLE FACILITIES

COMPANY/LOCATION	GENERATION RATE PER YEAR	AMOUNT STORED	REMARKS
FUEL FABRICATION: OPERATING FACILITIES			
Babcox & Wilcox (B&W)			
1. Apollo, PA: Converts UF ₆ to UO ₂ (ADU)	3.7x10 ² kg	None	Treated and released
2. Lynchburg, VA: UO ₂ powder from Apollo into fuel assemblies	None	None	No nitrate on site
Combustion Engineering			
1. Hematite, MO: Converts UF ₆ to UO ₂ (dry)	300 kg	None	Concreted, shipped to U.S. Ecology, Beatty, NV
2. Windsor, CT: UO ₂ powder from Hematite into fuel assemblies	None	None	No nitrates on site
Exxon			
Richland, WA *	Formal inquiry sent		
General Electric (GE)			
Wilmington, NC *	7.3x10 ⁴ kg	None	**Trucked off-site
Westinghouse			
Columbia, SC: Converts UF ₆ to UO ₂ (ADU and dry) and manufactures fuel assemblies	Formal inquiry sent		
General Atomic			
San Diego, CA: UO ₂ powder into HTGC reactor fuel assemblies	None	None	No nitrates on site
FUEL FABRICATION: NON-OPERATING FACILITIES			
U.N.C. Resources			
Wood River Junction, RI	None	12,000 drums concreted Ca(NO ₃) ₂	Previously stored in solar lagoon. Plant being decommissioned.
Westinghouse			
Cheswick, PA	None	63 drums concreted nitrates	Plant being decommissioned.

* Converts UF₆ to UO₂ (ADU) and manufactures fuel assemblies.

** After waste processing step and solar pond storage, the nitrate solution is trucked to a nearby paper mill and mixed with their waste. This can be readily done since radioactivity of waste is at-or-below background.

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

Kerr-McGee at Sequoyah, OK, uses the wet solvent extraction-fluorination process in their operation. The uranium concentrate is dissolved in nitric acid and aqueous-organic extraction used to prepare a high-purity uranium oxide feed. This feed is then put through the reduction, hydrofluorination, and fluorination steps. This process does result in the generation of a significant amount of nitrate wastes.

Initial waste processing steps produce an average of 600,000 gallons per month of acidic 1M nitrate solution. This solution is then neutralized with ammonia to a slightly basic pH. The resultant ammonium nitrate solution is decanted from precipitated sludge, treated with BaCl_2 to remove any residual activity, and pumped into storage lagoons. After concentration by solar evaporation, the ammonium nitrate solution is used to fertilize neighboring tracts of land. The only analysis performed on the waste is to ensure contained radioactivity is at or near background.

Enrichment

The uranium hexafluoride from conversion plants is processed at enrichment facilities to increase the isotopic concentration of U-235 in the gaseous uranium hexafluoride. In 1982, all three operational enrichment plants were of the Oak Ridge K-25 cascade that uses the gaseous diffusion process; all are government owned. [The K-25 process was shut down in 1987.] No nitric acid was used in the actual enrichment process. However, nitric acid is used for decontaminating cascade parts, dissolving miscellaneous solid uranium-containing wastes, and recovering gold from process equipment. The waste concentration nitric acid from the gold recovery operation is further treated to precipitate dissolved metals and transported to Oak Ridge for further process use. Other nitrate waste streams are treated and released.

Fuel Fabrication

Fuel fabricators received the enriched UF_6 (2-4% U-235) from the gaseous diffusion plants for conversion to UO_2 -containing light water reactor fuel. There have been six companies, listed back in Table 2, engaged in this part of the fuel cycle: Babcox and Wilcox, Combustion Engineering, Exxon, General Electric, Westinghouse, and General Atomic. Of these, only General Electric and Westinghouse are still operating. Babcox and Wilcox, Exxon, and General Electric used the wet ammonium-diuranate (ADU) process. In this process, the UF_6 is first hydrolyzed in deionized water to form UO_2F_2 . Ammonium hydroxide is added to precipitate ammonium diuranate, and this is calcined to UO_2 . After pelletizing operations, the UO_2 is loaded into Zircaloy fuel rods.

In the direct-dry process, which is used by the other facilities, UF_6 is processed through a series of retorts to form UO_4 . Reaction with hydrogen forms UO_2 powder and water vapor. The subsequent pelletizing steps are basically similar in both the wet and dry processes.

Table 3 lists the liquid wastes that are generated during processing of the uranium compounds and in the waste-treatment operations.

TABLE 3
LIQUID WASTES GENERATED DURING URANIUM PROCESSING
AND WASTE-TREATMENT OPERATIONS

1. General process liquids.
2. Large amounts of calcium fluoride formed during process waste treatment from neutralization of the fluoride originating in the UF₆ feed.
3. Nitrates generated by recovery of uranium from process equipment, filter sludges and, if incineration of combustibles is used, incinerator ash.

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

Information on the commercial nitrate wastes that was collected (by the authors of *Commercial and Defense Nitrate Wastes and Processing Alternatives*) is shown in Table 3. Where possible, this was ascertained by phone calls with cooperative facilities. Formal letters were sent to the others to collect the desired information. The generation of nitrate wastes is a function of the plant's fuel-rod production and a generalized estimation was made. Processing 5 MT per day of fuel would probably result in about 20 per cent of the product being recycled. Recycling would involve a nitric acid dissolution; processing of the resultant nitrate waste stream would give a product containing 730 kg per day NH₄NO₃ and 770 kg per day of the excess nitric acid. Operating at a nominal 220 days per year, the 5 MT per day operation would generate about 2×10^5 kg of waste nitrate per year.

Power Generation

Fuel assemblies from the fuel fabricators are loaded into commercial reactors and used in the generation of electricity. Power plants are not a significant source of nitrate wastes and no nitrate wastes from power plants were identified. Waste from reactor operations are treated and sent to near-surface burial sites operated by commercial waste-handling companies.

Fuel Reprocessing

Reprocessing of nuclear fuel is not presently a part of the nuclear-fuel cycle in the U.S. Two commercial reprocessing plants have been opened in this country: one at Barnwell, SC, was abandoned during construction and never operated on spent nuclear fuel, and the other at West Valley, NY. The West Valley facility did operate on spent fuel (generated 600,000 gallons of HLW) and was closed. The facility will soon be decommissioned. Waste generated and stored at this site, now under DOE jurisdiction, is covered in the Defense Waste section of this chapter. This waste is indicative of the large amount of nitrate wastes that would be generated if U.S. reprocessing becomes a reality.

Waste Disposal Sites

There is a small likelihood of finding any significant amount of nitrates in the waste now buried at any of the sites listed in Table 4. A study on the chemical toxicity of low-level wastes, which evaluated chemical species in the waste, found the amount of nitrates to be quite low. More evidence for this is provided by the analyses of water from survey trenches located at a typical site, where the concentrations of nitrates was found to be relatively low when compared to other cation concentrations. Since the solubility of nitrates in water is high compared to most other compounds, this is a significant finding.

Under present operating procedures at commercial sites, the majority of materials accepted for burial are classified under such broad categories as heavy sludges, evaporator bottoms, resin, etc. The isotopic content and total radiation levels are the major concern to site operators. A record search for nitrates listed in waste package inventories might reveal small amounts, but the effort would be costly.

TABLE 4
NITRATE INVENTORY AT COMMERCIAL SHALLOW-LAND-BURIAL SITES

LOCATION	SITE OPERATOR	NITRATE INVENTORY
Maxey Flats, KY Beatty, NV	Nuclear Engineering U.S. Ecology Co.*	Unknown. Probably some in with uranium, none per se.
Sheffield, IL	U.S. Ecology Co.*	Very little, if any. Policy not to accept rad waste if chemical toxicity greater hazard than rad activity.
Richland, WA	U.S. Ecology Co.*	No exact compositional inventory—could be small amount present.
Barnwell, SC	Chem-Nuclear Systems, Inc.	Probably some mixed with other wastes, none per se.
West Valley, NY	Nuclear Fuel Services	Covered in Defense Waste section of this chapter.**

* Formerly Nuclear Engineering Co.

** Much of this waste resulted from reprocessing fuel; therefore, it more closely resembles the defense waste.

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

DEFENSE NITRATE WASTES

A survey completed in FY81, and updated in 1984, indicated at least 250 million kilograms of nitrate waste are stored in the U.S., primarily in DOE facilities. A summary of the results is presented in Table 5. In addition to known amounts, there are also untabulated quantities of nitrate stored as effluents and salts in various tanks and ponds at DOE and commercial facilities. A large percentage of the stored nitrates is in the form of HLW at Savannah River Plant, Hanford Plant, Idaho Chemical Processing Plant (ICPP), and the West Valley Pilot Project (WVPP). The WVPP will be decommissioned, which could also generate large quantities of low-level nitrate waste in the near future.

Work is in progress to build the Defense Waste Processing Facility (DWPF) to remove fission products and actinide elements from the HLW stored at SRP and thus convert the bulk of the high-activity material to low-activity. Solidification of this low-activity waste (containing 59% nitrates and nitrites) using Portland cement (Saltstone) and disposal in near-surface facilities is being considered.

TABLE 5
SUMMARY OF NITRATE STORAGE AND GENERATION AT
DEFENSE FACILITIES

Site	Type	Stored Nitrate, kg	Generation Rate	Comments
Feed Materials Production Center	Effluent	--	2,200,000 ^a	Biode-nitrification planned
Hanford-Rockwell	Effluent	--	1,100,000 ^a	Discharged to ponds, cribs, etc.
Hanford-Rockwell	LLW, HLW, TRU	145,000,000 ^b	1,180,000 ^b	Stored in tanks
Hanford-United Nuclear	LLW	980,000 ^a	2,020,000 ^a	Discharged to solar ponds
Idaho Chemical Processing Plant	HLW	1,460,000 ^a	(24,000) ^a reduction	Liquid in tanks, NO _x released
Idaho Chemical Processing Plant	HLW	92,800 ^a	13,000 ^a	Calcine in bin sets
Idaho-Radioactive Waste Management Complex	LLW or TRU	11,300,000 ^b	-----	Buried or stored
Los Alamos National Laboratory	Effluents	-----	70,800 ^a	Discharged to canyon
Lawrence Livermore National Lab.	LLW	-----	<200 ^a	Cemented, shipped to NTS
Mound Facility	LLW	-----	1,500 ^c	Cemented, shipped to NTS
Nevada Test Site	LLW	10,400,000 ^b	-----	Receives RFP salts, FY78-FY85
Oak Ridge Y-12 Plant	Effluents	-----	664,000 ^a	Acid recycle biode-nitrification
Rocky Flats Plant	LLW	-----	930,000 to 2,050,000 ^b	Salts/saltcrete shipped to NTS
Rocky Flats Plant	LLW	1,450,000 ^b	-----	Solar ponds being decommissioned
Savannah River Plant	HLW	82,900,000 ^b	1,480,000 to 2,960,000 ^b	Grouting facility planned

TABLE 5 (CONT.)
SUMMARY OF NITRATE STORAGE AND GENERATION AT
DEFENSE FACILITIES

Site	Type	Stored Nitrate, kg	Generation Rate	Comments
TNS-Aerojet	LLW	82,900,000 ^b	38,000 ^a	Discharged to creek
West Valley Pilot Project	HLW	557,000 ^a	-----	Basic waste
West Valley Pilot Project	HLW	73,300 ^b	-----	Acidic waste
TOTALS		254,000,000	7,500,000 to 11,200,000	

^a Based on nitrate ion.

^b Based on nitrate compounds.

^c As cemented Fe(OH)₃ sludge

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP- 3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

Table 6 summarizes the quantities of nitrate/nitrite-contaminated waste at the DOE facilities. Table 7 summarizes the information on which these quantities are based.

TABLE 6
NITRATE/NITRITE WASTE QUANTITIES AT DOE FACILITIES

DOE SITE	TOTAL WASTE (10 ⁶ KG)	NITRATE (10 ⁶ KG)	NITRITE (10 ⁶ KG)	TOTAL NITRATE/NITRITE (10 ⁶ KG)
Hanford Site	781	110	14	124
Savannah River Plant	536	57	51	108
Idaho National Engineering Lab	9.2	2.1	0	2.1
Oak Ridge National Lab	1.0	0.22	0	0.22
Rocky Flats	23	0.071	0	0.071
TOTAL	1350	169	65	234

Source: KEI [Based on information from *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993.]

TABLE 7
BASIS FOR NITRATE/NITRITE WASTE QUANTITY ESTIMATION

DOE SITE	PH	DENSITY (G/ML)	VOLUME (10 ⁶ L)	NITRATE CONCEN- TRATION (G/L)	NITRITE CONCENTRA- TION (G/L)
Hanford Site	14	1.3	600	183	23
Savannah River Plant	14.5	1.41	380	149	133
Idaho National Engineering Lab	0.2	1.22	7.5	279	0
Oak Ridge National Lab	12.5	1.23	0.83	270	0
Rocky Flats	acidic	1.01	23	3.1	0
TOTAL			1011		

Source: KEI [Based on information from *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993.]

DOE is evaluating the following treatment scenario for the nitrate wastes: 1) retrieve the waste from the underground storage tanks, 2) pretreat to separate the high-activity/TRU components from the low-activity wastes, 3) treat the low-activity waste, which would contain nearly all of the nitrate, to immobilize or destroy the nitrate and dispose of the low-activity material in near-surface vaults, and 4) vitrify the high-activity/TRU waste and place the final waste in a Geologic Repository.

NOTE: There appears to be some confusion in the literature regarding *low- or high-level* waste as opposed to *low- or high-activity* waste. Unfortunately, the terms are often used interchangeably. [Refer to Appendix 2 for formal definitions of low- and high-level waste.] The definitions simply indicate the original source of the waste as opposed to the radioactive-material content (except for TRU elements, which have a limit of 100 nCi/g for LLW). The problem with the formal definitions, however, is that the radioactivity levels of high-level waste can be at background (i.e., "cold") and yet still be considered HLW while LLW may be much more "hot" radioactively. As a result, the formal definitions create much confusion. A more logical approach would be for HLW to represent radioactively "hot" waste and for LLW to represent "cold" waste.

Low-level Wastes

Low-level nitrate wastes are produced when nitric acid is used in the recovery and purification of actinide elements. After recovery of these elements, the acids are eventually neutralized by the addition of caustic during waste treatment operations, forming substantial quantities of sodium and/or potassium nitrate.

The basic sludge is usually removed by filtration. The nitrate salts were once deposited in solar ponds for evaporation. However, as a result of concentration by solar evaporation, large quantities of nitrates found their way into the environment by wind-blown spray and seepage from the ponds. Because of this, the use of ponds is no longer allowed by the EPA.

The present inventory of low-level nitrate wastes has been generated, for the most part, at RFP. Although RFP waste is originally acidic, its pH is adjusted to 11 with potassium hydroxide. The dried nitrate salts from RFP have been stored at INEL and NTS since 1973. The quantities and generation rates of this waste is shown in Table 8. Since 1973, RFP has been evaporating LLW nitrate solutions and drying the salts by drum dryer and spray dryer processes. These salts are very soluble and dispersible. Consequently, work is being conducted at RFP to convert this material to a more desirable waste form.

Although these salts comprise most of the tabulated low-level nitrate waste inventory, they do not constitute all of the LLW nitrates generated at DOE facilities because nitrates are still being produced at some facilities. Substantial quantities of these wastes were identified in a survey (W.W. Pitt, Jr., et al., *Survey of Needs for Biological Treatment of Radioactive Low-Level Liquids in Nuclear Facilities*, ORNL/NFW-70/76, 1980) conducted by ORNL researchers.

TABLE 8
LOW-LEVEL NITRATE WASTE EFFLUENTS GENERATED, STORED,
AND DISCHARGED FROM DOE FACILITIES

SITE	WASTE TYPE	VOLUME AND MASS STORED	WT.% NITRATE	GENERATION RATE
RFP	Basic solution and sludge in solar ponds	2.0x10 ⁴ m ³ 2.1x10 ⁷ kg	6.9*	4.0x10 ⁵ kg/yr (as spray-dried salts)
INEL	Dry nitrate salt	Unknown m ³ 1.8x10 ⁷ kg	93.0*	None
NTS	Dry nitrate salt from RFP 1978-1981	1.0x10 ⁴ m ³ 3.8x10 ⁶ kg	93.0*	Receives RFP salts
ORNL	Effluents	Unknown	N/A	1.5x10 ⁵ kg/yr**
Hanford	Effluents to pond	Unknown	N/A	2.48x10 ⁵ kg/yr**
LANL	Effluents	Unknown	N/A	5.0x10 ³ kg/yr**
NLO+	Effluents	Unknown	N/A	9.1x10 ⁴ kg/yr**

* Based on NO₃ compounds.

** Shown as NO₃-N.

+ National Lead Company of Ohio

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

In general, DOE contractors are still meeting EPA standards (by various means) or operating under variances. However, the continued discharge of these effluents is becoming increasingly difficult as stricter controls are applied to environmentally potentially hazardous materials. In addition, the present trend is toward "near zero release" of any waste to the environment from nuclear facilities.

The volume of the LLW nitrate salts and effluents are substantial, but another huge inventory of nitrates also exists in the U.S.—the HLW stored at the various DOE facilities. These HLWs must be taken into consideration with any study on low-level nitrate wastes,

since the greater part of the high-activity HLW mass may be converted to the low-activity category when they are eventually processed for the removal of fission products.

High-level Wastes

High-level waste is, by definition, the front-end aqueous waste from the reprocessing of irradiated nuclear fuel. The bulk of the wastes was produced in the production of plutonium for nuclear weapons, but a minor amount was also derived from the reprocessing of commercial reactor fuel. The waste usually consists of basic liquid, sludge, and salts or an acid liquid with very little solid residue. The category also includes calcined material or other secondary products that are generated as HLW, which are dewatered and concentrated for storage. This waste contains fission products that produce heat and also necessitate substantial radiation shielding.

All the HLW in the U.S. is stored at the Hanford Plant, Idaho Chemical Processing Plant (ICPP), SRP, and the Western New York Nuclear Service Center (WNYNSC). The WNYNSC was originally engaged in reprocessing commercial reactor fuels, but it was subsequently shut down. The commercial waste is now stored under DOE jurisdiction at WNYNSC. A large inventory of spent nuclear fuel is now stored in the U.S., and the WNYNSC wastes are an indication of the great amount of waste nitrates that would be generated if reprocessing of commercial fuel is resumed.

Consolidation and Concentration

Each of these facilities mentioned above, except WNYNSC, is in the process of consolidating and concentrating the HLW now stored. Note that there is no HLW on the Oak Ridge Reservation.

Hanford

At Hanford, a large portion of the heat-producing isotopes, Sr-90 and Cs-137, have been removed and placed in capsules for storage in water basins. The remaining liquid, sludge, and salt cake are stored in underground tanks.

Idaho National Engineering Laboratory

The ICPP waste differs from the Hanford and SRP wastes in that it is in an acid form rather than basic. At ICPP, the waste is calcined to a granular material in a fluidized-bed process. For this reason, the inventory of ICPP acid liquid sludge and salt will decrease in the future. However, the inventory of calcined granules will be increased by the process.

Savannah River Plant

At SRP, excess liquids are drawn off the sludge and evaporated. The evaporator bottoms are returned to a tank and allowed to solidify into a salt cake. Any excess water with the salt cake is returned to the evaporator for further concentration.

Western New York Nuclear Service Center

No waste treatment processes are currently in effect at WNYNSC. In October 1980, DOE began a high-level liquid nuclear waste management demonstration project at the facility. A facility to solidify the HLW stored at the site is under construction.

Conversion of High-activity Waste to Low-activity

The reason for including HLW in this study is based on the assumption that the fission products may be separated from the material in the future, leaving a great quantity of low-activity, high-nitrate waste. Since plans for separating the fission products from the bulk of the HLW are now in progress at one DOE facility, it seems advisable to assume that all the HLW could eventually be processed for fission product removal.

According to Jon Cruse (personal communication with KED) at Westinghouse Hanford, around 80 per cent of the high-activity HLW volume will be converted to low-activity. Currently, the plan is to have separate treatment facilities for the low- and high-activity wastes.

The amounts and generation rates of HLW are presented in Table 9 and represents the best estimates possible under fluctuating conditions. When the radioactive isotopes are removed, these figures could be reduced somewhat; consequently, they represent the maximum amount of materials that may require reprocessing in the LLW category. With the exception of WNYNSC, all of the HLW in storage are being concentrated in continuous processes that change the volumes and concentrations daily. This fact makes the calculation of generation rates and future inventory projections very difficult.

TABLE 9
NITRATE HLW GENERATED AND STORED AT DOE FACILITIES

SITE*	WASTE TYPE	VOLUME AND MASS STORED	WT.% NITRATE	GENERATION RATE
SRP	Basic nitrate liquid, sludge, and salt cake	1.0x10 ⁵ m ³ 1.4x10 ⁸ kg	59.2**	2.5 to 5.0x10 ⁶ kg/yr
Hanford	Basic nitrate liquid, sludge, and salt cake	1.9x10 ⁵ m ³ 2.7x10 ⁸ kg	53.7**	2.5x10 ⁶ kg/yr (avg. through 1990)
ICPP	Acid nitrate liquid, sludge, and salt cake	9.3x10 ³ m ³ 1.1x10 ⁷ kg	74.0***	1.8x10 ⁵ kg/yr (reduction, avg. through 2000)
ICPP	Granular calcine	2.1x10 ³ m ³ 2.9x10 ⁶ kg	3.8***	4.2x10 ⁵ kg/yr
WNYNSC	Basic nitrate liquid, sludge, and salt cake	2.1x10 ³ m ³ Unknown mass	Liquid- 43.0**/ Sludge- unknown	None
WNYNSC	Nitric acid liquid	45 m ³ 8.1x10 ⁴ kg	90.5**	None

* Refer to section, "Nitrate Waste Compositions," for more details on waste at each site.

** Based on NO₃ compounds.

*** Shown as NO₃-N.

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

Nitrate Waste Compositions

According to *Evaluation of Nitrate Destruction Methods* (DOE/MWIP-10, March 1993), the wastes stored at the Hanford Site, ORNL, and SRP are all high-nitrate-concentration alkaline solutions. Rocky Flats and Idaho wastes are both acidic. Table 10 describes the wastes found at the various facilities.

TABLE 10
DOE NITRATE WASTE OVERVIEW

DOE SITE	NITRATE CONCENTRATION	ACIDIC/ALKALINE	OTHER SIGNIFICANT CONTAMINANTS
Hanford Site	High	Alkaline	Highest concentration of total organic carbon
Idaho National Engineering Lab	Very High	Acidic	Chromium and mercury
Oak Ridge National Lab	High	Alkaline	Highest concentration of potassium
Rocky Flats	Low	Acidic	
Savannah River Plant	Very High	Alkaline	Highest sodium and nitrate concentration

Source: Derived by KEI from *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993.

While the acidic wastes typically do not contain any solids, the alkaline wastes have separated into three parts:

- Chemical sludge containing most of the metals, transuranics, and radionuclides;
- Salt cake consisting mainly of solid sodium nitrate with lower levels of metals and organics;
- Concentrated aqueous supernatant, whose composition is in equilibrium with the sludge and salt cake.

The ORNL waste has the highest concentration of potassium, while the Hanford site waste has the highest concentration of total organic carbon. The SRP waste has the highest sodium and nitrite concentrations. The INEL waste is acidic, has a very high nitrate concentration, and contains significant concentrations of chromium and mercury. The waste at RFP is much more dilute; it is currently dried and then mixed with cement before storage. The composition data for Hanford, ORNL, and RFP are overall averages, while the data for INEL and SRP are for one specific tank. However, at all of the sites, the waste composition varies widely among tanks.

The high-level wastes at the storage facilities contain different residues from various processing techniques used over the years. Special recovery campaigns have produced wastes that vary greatly from Purex process wastes. However, all the HLW have one thing in common—huge quantities of nitrate compounds.

The bulk of the wastes were produced in the production of plutonium for nuclear weapons, but a minor amount was also derived from the reprocessing of commercial reactor fuel. The waste usually consists of basic liquid, sludge, and salts or an acid liquid with very little solid residue. The category also includes calcined material or other secondary products that are generated as HLW, which are dewatered and concentrated for storage. This waste contains fission products that produce heat and also necessitate substantial radiation shielding.

Most of the wastes contain uranium and transuranic elements, radioactive isotopes (cesium, strontium) resulting from their decay, and nitrates from the nitric acid used in processing. There may also be some organic contaminants and metals such as chromium, zirconium, and bismuth. Estimated compositions of HLW in weight per cent for selected DOE facilities are summarized in Tables 11 and 12. The concentrations shown in these tables indicate that nitrate compounds are the largest single component in the HLW. Table 11 summarizes the estimated HLW ion composition in weight per cent and 12 summarizes the weight per cents by compound.

All the HLW in the U.S. is stored at the Hanford Plant, Idaho Chemical Processing Plant (ICPP), SRP, and the Western New York Nuclear Service Center (WNYNSC). The WNYNSC was originally engaged in reprocessing commercial reactor fuels, but it was subsequently shut down. The facility generated around 600,000 gallons of waste. The commercial waste is now stored under DOE jurisdiction at WNYNSC. A large inventory of spent nuclear fuel is now stored in the U.S., and the WNYNSC wastes are an indication of the great amount of waste nitrates that would be generated if reprocessing of commercial fuel is resumed.

TABLE 11
ESTIMATED ION-COMPOSITION OF HIGH-LEVEL WASTES (WT.%)

	FACILITY			
	ICPP	WNYNSC	SRP	HANFORD
Na	17.1	26.6	30.1	26.3
K	1.0	----	----	----
NO ₃	64.7	61.1	44.1	49.7
Cl	0.1	----	----	----
SO ₄	1.2	4.0	5.3	0.3
PO ₄	----	1.8	----	4.3
F	4.6	----	----	----
Other solids	11.26	6.5	20.5	19.4

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

TABLE 12
ESTIMATED COMPOSITION OF HIGH-LEVEL WASTES (WT.%)

COMPOUND	WNYNSC	FACILITY	
		SRP	HANFORD
NaNO ₃	83.72*	60.45	68.09
NaNO ₂	-----	2.98	4.07
Na ₂ CO ₃	-----	2.89	1.44
NaOH	1.83	8.62	7.35
NaAlO ₂	-----	12.72	5.12
Na ₂ SO ₄	6.90	9.18	0.52
Na ₃ PO ₄	-----	-----	7.43
FePO ₄	2.89	-----	-----
MnO ₂	0.17	0.38	0.09
Hg	-----	0.10	-----
Fe(OH) ₃	3.80	1.61	0.59
Al(OH) ₃	0.06	-----	1.13
Other solids	1.88	1.68	3.93

* NaNO₃ - NaNO₂ combined.

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

The following sections present the composition data gathered by KEI for each of the facilities known to have aqueous nitrate tank waste.

Hanford

National defense activities have generated radioactive waste since 1944 on the Hanford Site in Washington State. Liquid radioactive and chemical wastes from nuclear material production and research activities were transferred to underground, reinforced-concrete, steel-lined tanks [commonly referred to as single-shell tanks (SSTs) and double-shell tanks (DSTs)] for storage. Since 1980, only stabilization and isolation activities have occurred in the SSTs. The tank system consists of 177 tanks grouped in 18 tank farms.

Hanford wastes can be subdivided into HLW, TRU, and LLW. The HLW and TRU wastes are targeted for vitrification and the LLW is targeted for cement-based grout, although a final decision is not expected until 1996. The LLW contains most of the sodium nitrate and would be grouted in near-surface vaults, in a similar fashion to efforts at Savannah River using "salt stone." Table 13 lists the compositions of the contaminants found in the Hanford Plant high-level waste tank supernate. The data in this table is based on dissolving the existing solid salt cake and supernate into a 5 M sodium solution resulting in an overall volume of 600 million liters.

TABLE 13
COMPOSITION OF HANFORD PLANT HIGH-LEVEL WASTE TANK
SUPERNATE

CONTAMINANT	CONCENTRATION		QUANTITY	
	g/L	Bq/L	g	Bq
Nitrate	183		1.10E11	
Sodium	115		6.90E10	
Hydroxide	32		1.92E10	
Nitrite	23		1.38E10	
Phosphate	8.0		4.80E09	
Carbonate	3.9		2.34E09	
Sulfate	2.8		1.68E09	
Total Organic Carbon	2.6		1.56E09	
Aluminum	2.3		1.38E09	
Potassium	1.8		1.08E09	
Fluoride	1.3		7.80E08	
Chloride	0.06		3.60E07	
TOTAL	375.8		2.26E11	
¹³⁷ Cs		9.4E8		5.6E17
⁹⁰ Sr		3.1E7		1.9E16
⁹⁹ Tc		9.4E5		5.6E14
²⁴¹ Am		2.5E5		1.5E14
²³⁹ Pu		2.5E4		1.5E13
TOTAL		9.7E8		5.8E17

** Volume and conc. data are based on dissolving the existing solid salt cake and supernate into a 5 M sodium solution (volume, 600 million liters; density, 1.3 g/ml; pH, 14).

Source: *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993. [Original source: *Final Environmental Impact Statement: Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes*, DOE/EIS-0113, December 1987.]

The LLW feed baseline will be comprised of supernatant liquid and wash solutions. Pretreatment for Cs removal and possibly Sr, Tc, and TRU removal will be done prior to nitrate destruction. Currently, the plan for nitrate destruction and immobilization is to use the Combustion-fired Melter (CFM) and the Liquid-fed Ceramic Melter (LFCM). The baseline waste forms are cullet in binder (e.g., sulfur polymer cement) and glass monolith. Off-gas treatment requirements will include semi-volatile nuclides (e.g., Cs, Tc, I, NO_x, SO₂, and particulates).

Uncertainties associated with the Hanford baseline are the feed composition, vitrification system performance, off-gas treatment system, and the waste product requirement. The feed composition is uncertain (incomplete characterization, unknown impacts of pre

treatment) and likely to be variable. Because of limited solubility of some tank constituents (e.g., Cr, phosphate), the LLW volume may increase or need another waste form.

Conversion from HLW to LLW

According to *Hanford Site Tank Waste Remediation System Technical Strategy* (3/18/94), the plan is to separate the tank waste into HLW/transuranic waste and LLW fractions. Most of the radionuclides and only a small part of the other waste materials are in the HLW and the remainder is in the LLW. Radionuclides will be removed from the waste stream destined to become LLW to the extent needed to:

- Meet the NRC's "incidental waste" classification,
- Meet DOE's LLW disposal requirements, which include an ALARA policy and an acceptable disposal system performance assessment,
- Be less than the comparable limits for commercial LLW (10 CFR 61 class C waste),
- Permit construction of a lightly shielded LLW vitrification facility if practical.

For radionuclides, the LLW feed stream specification to the LLW Vitrification Facility will be met if cesium¹³⁷ is reduced to 1 curie per m³ (thought to be the level practically achievable) and strontium⁹⁰ is removed when necessary.

The primary method to separate the waste into HLW and LLW fractions will be sludge washing and solid-liquid separation. The primary radionuclide removal method for the liquid fraction, which is destined to become the LLW stream, will be ion exchange. An ion exchange cesium removal demonstration system will be initially deployed. Development will continue for selected processes to remove long-lived radionuclides (⁹⁹Tc, etc.) from the LLW stream until implemented or determined not to be needed. Organic destruction process development will continue as a contingency until it is implemented or until it is determined that it is not needed.

The vitrified LLW will be disposed of on-site, near-surface, in a form that will allow retrieval for placement elsewhere (for up to 50 years) and in conformance to DOE disposal requirements. The vitrified HLW/TRU waste will be placed in canisters that meet the Geologic Repository Program's waste acceptance criteria and stored until they can be shipped to a geologic repository for disposal. The strontium and cesium capsules will be stored until they can be packaged (or processed) in a manner that conforms to the Geologic Repository Program Requirements and shipped to a repository for disposal.

Single-shell Tank Waste

The SSTs contain primarily inorganic waste, although relatively small amounts of plant solvents were entrained during fuel reprocessing. Also, water-soluble complexing agents and carboxylic acids added in the B Plant fractionation process are in some SST wastes. Hanford plans to retrieve the SST waste by 2018, close all SSTs by 2024, and complete immobilization of all waste by 2028.

Chemicals. A listing of all non-radioactive chemicals known to have been used at production plants and support facilities that transferred waste to SSTs has been documented in *Inventory of Chemicals Used at Hanford Production Plants and Support Operations (1944-1980)*.

Specific chemicals that may have been transferred to the SSTs and that appear on the *Dangerous Waste Sources List* (WAC 173-303-9904) include carbon tetrachloride, methylene chloride, hexone, acetone, and ethyl ether. Only chemicals from the sources numbered F001, F002, F003, and F005 are likely to be found in the SSTs. Chemical reactions (e.g., oxidation-reduction, neutralization, precipitation) and radiolysis have converted many of these chemicals into different compounds. Dangerous waste sources are discussed in WAC 173-303-082 and listed in WAC 173-303-9904.

The SST portion of the system consists of 149 tanks grouped in 12 tank farms. The 149 SSTs contain $140,000 \text{ m}^3$ (37 Mgal) of waste. It contains a total of $2.29 \times 10^8 \text{ kg}$ of chemicals and $5.5 \times 10^{18} \text{ Bq}$ ($1.5 \times 10^8 \text{ Ci}$) of radionuclides in the following fractions:

- $2,300 \text{ m}^3$ (600,000 gal.) supernatant
- $89,000 \text{ m}^3$ (23 Mgal.) salt cake (approx. 93 wt.% NaNO_3 and NaNO_2)
- $48,000 \text{ m}^3$ (12 Mgal) sludge (hydrous metal oxides, 50% salt cake)

The salt cake consists primarily sodium nitrate and sodium nitrite. The sludge consists of the hydrous metal oxide solids precipitated from the neutralization of acid waste before being transferred to the SSTs. On transfer of the evaporator slurry into the SSTs, some of the salt precipitated with the sludge. As a result of the precipitating salt, roughly 50 per cent of the reported sludge volume is salt cake. The liquid solution exists as supernatant and interstitial liquid in the tanks. An estimated $23,000 \text{ m}^3$ (6 Mgal.) of drainable interstitial liquid is present in SST salt cake and sludge. Table 14 shows the chemical inventories associated with existing SST wastes.

TABLE 14
CHEMICAL INVENTORIES ASSOCIATED WITH EXISTING
HANFORD SINGLE-SHELL TANK WASTES

CHEMICAL COMPONENT ^a	TOTAL SLUDGE (MG)	TOTAL SALT CAKE (MG)	INTERSTITIAL LIQUID (MG)
Na ⁺	15,000	34,000	2,300
Al ⁺³ (b)	1,100	630	490
Ce ⁺³	230		
Cr ^{+3,+6}	96		
Cd ⁺²	4		
Fe ⁺³	630		
Sr ⁺²	36		
Bi ⁺³	260		
Ca ⁺²	130		
Hg ⁺	1		
Cl ⁻	40		
F ⁻	800		5
NO ₃ ⁻	15,000	80,000	1,800
NO	2,000	1,500	1,300
PO ₄ ⁻³	7,400	1,200	160
OH ⁻	4,100	850	310
SO ₄ ⁻²	500	1,100	
CO ₃ ⁻²	1,200	410	40
MnO ₂	190		
Ni ₂ Fe(CN) ₆	500		
P ₂ O ₅ •24WO ₂ •44H ₂ O	20		
ZrO ₂ •2H ₂ O	430		
Organic carbon			200
Cancrinite ^c	2,700		
H ₂ O	26,000	14,000	4,800
TOTAL ^d	78,000	134,000	11,000

NOTE: Most minor components (<100 Mg total) are not listed.

^a Values taken from RHO-RE-ST-30P, Table 2-5 (RHO 1985).

^b Aluminum is present as Al⁺³ and as AlO₂⁻, but is listed as Al⁺³.

^c Known silica additions are assumed to have reacted with aluminates and hydroxides to form cancrinite (assumed to be 2NaAlSiO₄•0.52NaNO₃•0.68H₂O).

^d Totals are rounded. Totals do not match RHO-RE-ST-30P (RHO 1985) because of AlO₂⁻ being listed as Al⁺³.

Source: *Tank Waste Technical Options Report*, Team leader: K.D. Boomer, Westinghouse Hanford Co. for the Dept. of Energy Office of Environmental Restoration and Waste Management, WHC-EP-0616 Rev. 0, March 31, 1993.

Radionuclides. Table 15 lists estimates of SST radionuclide inventories.

TABLE 15
EXISTING HANFORD SST TANK WASTE RADIONUCLIDE
INVENTORY (DECAYED TO DECEMBER 1990^a)

RADIONUCLIDE	RADIOACTIVITY TOTAL (CI)	HALF-LIFE (YEARS)
²⁴¹ Am	4.6E+04	430
²⁴³ Am	1.9E+01	7,900
¹⁴ C	3.0E+03	5,700
²⁴⁴ Cm	1.6E+02	18
¹³⁷ Cs, ¹³⁷ Ba	3.5E+07	30
¹²⁹ I	2.4E+01	17,000,000
⁶³ Ni	3.0E+05	92
²³⁷ Np	3.2E+01	2,100,000
²³⁸ Pu	4.5E+02	87
²³⁹ Pu	2.2E+04	24,000
²⁴⁰ Pu	5.4E+03	6,600
²⁴¹ Pu	5.7E+04	14
¹⁰⁶ Ru	2.3E+01	1
¹⁵¹ Sm	6.8E+05	87
¹²⁶ Sn	5.7E+02	10,000
⁹⁰ Sr, ⁹⁰ Y	1.13E+08	28
⁹⁹ Tc	1.6E+04	210,000
²³⁵ U	2.0E+01	7.1E+08
²³⁸ U	4.6E+02	4.5E+09
⁹³ Zr	4.3E+03	1,500,000

Note: To convert Ci to Bq, multiply by 3.7E+10.

^a Values decayed to December 1990 (RHO 1985, DOE 1991); decay daughters are included for ¹³⁷Cs and ⁹⁰Sr.

Source: *Tank Waste Technical Options Report*, Team leader: K.D. Boomer, Westinghouse Hanford Co. for the Dept. of Energy Office of Environmental Restoration and Waste Management, WHC-EP-0616 Rev. 0, March 31, 1993.

Double-shell Tank Waste

Sufficient double-shell tank storage capacity will be maintained to support safety issue resolution; waste retrieval, pretreatment, and immobilization; and Hanford Site cleanup. Additional DSTs will be constructed as needed.

DSTs will continue to receive newly generated waste from facilities and pumpable liquids from the SSTs. In the future, they will receive wastes retrieved from SSTs and DSTs and from waste pretreatment and immobilization operations. DST waste volumes will be minimized while keeping incompatible wastes segregated and the 242-A Evaporator will operate as needed.

Chemicals. All of the DST wastes consist of a liquid portion and a solid portion. The 28 DSTs contain 91,000 m³ (24 Mgal.) of waste, which is classified into the following five types:

- 7,200 m³ (1.9 Mgal.) is neutralized current acid waste (NCAW)
- 2,200 m³ (590,000 gal.) neutralized cladding removal waste (NCRW)
- 416 m³ (110,000 gal.) Plutonium Finishing Plant (PFP) waste
- 18,000 m³ (4.8 Mgal.) complexant concentrate (CC) waste
- 65,000 m³ (17 Mgal.) is double-shell slurry (DSS), double-shell slurry feed (DSSF), concentrated phosphate, and dilute non-complexed wastes

The NCAW resulted when concentrated acidic PUREX process high-level radioactive waste was made alkaline and stored in DSTs (generated between 1983 and 1988). An NH₄NO₃-NH₄F solution was used in the PUREX Plant during 1983 and 1988 to dissolve zircaloy cladding from N Reactor fuel. The NCRW resulted when the spent cladding waste was made alkaline and stored in DSTs. The PFP waste resulted when composite acidic waste from the PFP was made alkaline. The CC waste is the concentrated aqueous raffinate from ⁹⁰Sr liquid-liquid extraction operations performed in the 1960's and 1970's. The CC waste has a very high concentration of organic chelating agents and their degradation products. The DSS and DSSF are viscous, highly alkaline liquid wastes containing high concentrations of sodium salts generated from evaporation of dilute solutions.

The solid portion of NCAW, NCRW, CC waste, and PFP waste all contain >3,700 Bq/g (>100 nCi/g) transuranic elements. The NCAW solids also contain >99 per cent of the ⁹⁰Sr present in the PUREX process HLW. Other DST solid wastes do not contain large concentrations of ⁹⁰Sr. The NCAW and CC alkaline waste solutions contain relatively high concentrations of ¹³⁷Cs. Because of the presence of large amounts of organic complexants, alkaline CC waste supernatants also contain >3,700 Bq/g (>100 nCi/g) transuranic elements.

TABLE 16
CHEMICAL INVENTORIES ASSOCIATED WITH EXISTING
HANFORD DOUBLE-SHELL TANK WASTES

CHEMICALS	TOTAL SLUDGE (MG)
Ag ⁺	0.441
Al ⁺	2,040
As ⁺⁵	0.841
B ⁺³	2.55
Ba ⁺²	1.73
Be ⁺²	0.0100
Ca ⁺²	15.9
Cd ⁺²	6.71
Cl ⁻	394
Co ⁺³	0.814
CO ₃ ⁻²	1,070
Cr ^{+3,+6}	65.1
Cs ⁺	0.85
Cu ⁺²	1.23
F ⁻	293
Fe ⁺³	102
Fe(CN) ₆ ⁻³	1.23
H ₂ O	53,300
Hg ⁺²	0.253
K ⁺	1,090
Mg ⁺²	5.33
MnO ₂	22.2
Mo ⁺⁶	8.15
Na ⁺	15,700
Ni ⁺³	10.5
NO ₂ ⁻	4,770
NO ₃ ⁻	12,600
OH ⁻	9,770
Pb ⁺⁴	3.43
PO ₄ ⁻³	213
Rare earths ⁺³	11.6
Rh ⁺³	0.442
Ru ⁺³	0.553
Si ⁺⁴	58.2
SO ₄ ⁻²	356
Th ⁺⁴	0.826
Ti ⁺⁴	0.445
Total organic carbon	599
UO ₂ ⁺²	43.5
Zn ⁺²	2.26
ZrO ₂ •H ₂ O	546
TOTAL	103,000

Source: *Tank Waste Technical Options Report*, Team leader: K.D. Boomer, Westinghouse Hanford Co. for the Dept. of Energy Office of Environmental Restoration and Waste Management, WHC-EP-0616 Rev. 0, March 31, 1993.

Radionuclides. Table 17 lists estimates of DST radionuclide inventories.

TABLE 17
EXISTING HANFORD DST TANK WASTE RADIONUCLIDE
INVENTORY (DECAYED TO DECEMBER 1990^a)

RADIONUCLIDE	RADIOACTIVITY TOTAL (CI)	HALF-LIFE (YEARS)
²⁴¹ Am	9.9E+04	430
¹⁴ C	2.3E+03	5,700
¹³⁷ Cs, ¹³⁷ Ba	6.6E+07	30
¹²⁹ I	2.7E+01	17,000,000
²³⁹ Pu	2.3E+04 ^b	24,000
⁹⁰ Sr, ⁹⁰ Y	2.6E+07	28
⁹⁹ Tc	2.5E+04	210,000

Note: To convert Ci to Bq, multiply by 3.7E+10.

^a Values decayed to December 1990 (RHO 1985, DOE 1991); decay daughters are included for ¹³⁷Cs and ⁹⁰Sr.

^b Values also includes ²⁴⁰Pu.

Source: *Tank Waste Technical Options Report*, Team leader: K.D. Boomer, Westinghouse Hanford Co. for the Dept. of Energy Office of Environmental Restoration and Waste Management, WHC-EP-0616 Rev. 0, March 31, 1993.

Idaho National Engineering Laboratory

Table 18 lists the compositions of the contaminants found in the INEL high-level waste tank supernate.

TABLE 18
COMPOSITION OF INEL HIGH-LEVEL WASTE TANK SUPERNATE

CONTAMINANT	CONCENTRATION		QUANTITY	
	g/L	Bq/L	g	Bq
Nitrate	279		2.09E09	
Sodium	17.9		1.34E08	
Aluminum	14.0		1.05E08	
Potassium	3.9		2.93E07	
Iron	3.0		2.25E07	
Hydrogen ion	1.8		1.35E07	
Calcium	1.6		1.20E07	
Fluoride	0.8		6.00E06	
Chromium	0.7		5.25E06	
Mercury	0.6		4.50E06	
TOTAL	323.3		2.42E09	
¹³⁷ Cs		9.9E09		7.4E16
⁹⁰ Sr		8.2E09		6.2E16
¹⁵⁴ Eu, ¹⁵⁵ Eu		1.3E08		9.8E14
¹⁴⁴ Ce		8.7E07		6.5E14
⁶⁰ Co		1.8E06		1.4E13
TOTAL		1.8E10		1.4E17

Supernate volume, 7.5 million liters; Density, 1.22 g/ml; pH, 0.2

Source: *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993. [Original source: Chris Kent, INEL, personal communication to P.A. Taylor, ORNL, Feb. 4, 1993.]

Oak Ridge National Laboratory

Table 19 lists the compositions of the contaminants found in ORNL low-level liquid waste Melton Valley Storage Tank (MVST) supernate (volume, 830,000 liters; density, 1.23 g/ml; pH, 12.5).

TABLE 19
COMPOSITION OF ORNL LOW-LEVEL LIQUID WASTE MELTON
VALLEY STORAGE TANK SUPERNATE
(Average composition of 10 tanks)

CONTAMINANT	CONCENTRATION		QUANTITY	
	g/L	Bq/L	g	Bq
Nitrate	270		2.24E08	
Sodium	88		7.30E07	
Potassium	24		1.99E07	
Carbonate	6.9		5.73E06	
Calcium	3.4		2.82E06	
Chloride	2.9		2.41E06	
Magnesium	0.7		5.81E05	
Total organic carbon	0.6		4.98E05	
Uranium	0.2		1.66E05	
TOTAL	396.7		3.29E08	
¹³⁷ Cs		4.8E8		4.0E14
⁹⁰ Sr		4.1E7		3.4E13
¹³⁴ Cs		5.0E6		4.2E12
⁶⁰ Co		3.4E6		2.8E12
¹⁰⁶ Ru		8.7E5		7.2E11
Gross alpha		3.3E5		2.7E11
¹⁴ C		1.9E5		1.6E11
TOTAL		5.3E8		4.4E14

Source: *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993. [Original source: M.B. Sears, et al., *Sampling and Analysis of Radioactive Liquid Wastes and Sludges in the Melton Valley and Evaporator Facility Storage Tanks at ORNL*, ORNL/TM-11652, Martin Marietta Energy Systems, Sept. 1990.]

Rocky Flats

Rocky Flats Plant (RFP) generates large quantities of nitrate waste solutions during the processing of nuclear materials. After processing through the waste treatment plant, the very low-level radioactive effluents were originally stored in solar ponds. A large evaporation system was later installed to evaporate the diluted solutions to about 35 per cent total dissolved solids content, the concentration limit for efficient operation of the evaporator. The evaporator concentrate is then processed through a spray dryer and the dry salts boxed for shipment off-site.

Table 20 lists the compositions of the contaminants found in the Rocky Flats Plant's nitrate waste (volume, 23 million liters/year; density, 1.01 g/ml; pH, acidic).

TABLE 20
COMPOSITION OF ROCKY FLATS PLANT NITRATE SALT WASTE

CONTAMINANT	CONCENTRATION		QUANTITY	
	g/L	Bq/L	kg/year	Bq/year
Nitrate	3.1		7.13E04	
Sodium	1.6		3.68E04	
Chloride	1.4		3.22E04	
Sulfate	1.4		3.22E04	
Potassium	1.1		2.53E04	
Carbonate	0.7		1.61E04	
Calcium	0.5		1.15E04	
Fluoride	0.3		6.90E03	
Iron	0.3		6.90E03	
TOTAL	10.4		2.39E05	
Plutonium (total)		500		1.15E10

Source: *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993. [Original source: A. Faucet, Rocky Flats Plant, Golden, CO, personal communication to P.A. Taylor, ORNL, March 24, 1993.]

The spray-dried nitrate salts are in the form of a very fine powder. A decision had been made to immobilize the salts prior to shipment, as the fine powder is easily dispersible, very soluble, and an oxidizer. Acceptance criteria at the burial site no longer permit burial of the unstabilized loose powder.

While the simplest production option was to directly cement the evaporator concentrate and eliminate the spray dryer step, the necessity for off-site shipment of the waste made this choice unacceptable. Direct cementing of the 35 per cent concentrate would produce a waste form containing about 13 per cent waste solids, requiring 7.5 times more shipments and adding 7.5 times more weight than is the case with the dry salt. The formulation as is now produced (54% salts) results in about a doubling of weight and shipping costs. The RFP generates a large amount of nitrate salts annually (1,000,000 kg/yr) and the necessity of off-site shipment made the amount of added weight due to processing quite important. Because

high structural strength is not required, the added cement content could be minimized. Table 21 shows the composition of the dried nitrate waste.

TABLE 21
COMPOSITION OF RFP SPRAY-DRIED NITRATE WASTE

COMPOUND	WT. %
NaNO ₃	53.9
KNO ₃	33.9
NaCl	3.2
K ₂ SO ₄	2.8
KCl	2.2
K ₂ SO ₄	1.8
Na ₃ PO ₄	0.9
K ₃ PO ₄	0.6
NaF	0.4
KF	0.3

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

Savannah River

Defense high-level radioactive waste has been generated at the Savannah River Site, located near Aiken, SC, from processing irradiated reactor fuel to produce nuclear materials for national defense.

Since start-up, over 400 million liters of high-level waste have been generated. This waste has been evaporated to about 130 million liters, which is now stored in large underground tanks. Additional waste will be generated through the year 2000. This interim storage mode requires active maintenance, surveillance, and other operations to minimize releases of radioactive material to the environment. The tanks have a limited life and must be replaced periodically.

As part of the process for the Defense Waste Processing Facility (DWPF) at Savannah River, the accumulated high-level nitrate wastes in the large storage tanks will be slurried, pumped out, and decontaminated. Decontamination will remove most of the cesium, strontium, and transuranics resulting in a low-activity waste the average composition shown in Table 22. The large concentration of NaNO₂ is due to radiological effect of contained radioactive nuclides on the initial NaNO₃. Total radionuclide concentration in the decontaminated waste will be about 190 nCi/g.

The principal radionuclides in the waste are ⁹⁰Sr and ¹³⁷Cs. Approximately 10 per cent of the waste consists of iron, manganese, uranium, and aluminum oxides and hydroxides, which are precipitated upon neutralization of the acidic nitric acid wastes produced in the chemical separation operations. These solids are referred to as sludge. The sludge contains most of the strontium and small amounts of actinides not recovered in the reprocessing plants. The remainder of the waste is liquid and salt cake, which consists primarily of

sodium nitrate, sodium nitrite, sodium aluminate, and sodium hydroxide. This waste contains ^{137}Cs and traces of other soluble radionuclides.

The HLW will be pretreated (referred to as In-tank Processing) to reduce the amount of waste that is disposed of in the high-cost borosilicate glass waste form. This pretreatment will concentrate the radionuclides in a small volume for vitrification. The remaining high-volume, low-level waste will be disposed of in a cement waste form referred to as saltstone.

TABLE 22
AVERAGE CHEMICAL COMPOSITION OF SAVANNAH RIVER
PLANT DECONTAMINATED, AGED SALT SOLUTION

COMPONENT	DECONTAMINATED SALT SOLUTION* (WT.%)
H_2O	68
NaNO_3	15.6
NaOH	4.2
NaNO_2	3.9
$\text{NaAl}(\text{OH})_4$	3.6
Na_2SO_4	1.9
NaCO_3	1.7
$\text{Na}_2\text{C}_2\text{O}_4$	0.31
Other salts	0.20
Na_3PO_4	0.13
NaCl	0.12
$\text{NaB}(\text{C}_6\text{H}_5)_4$	0.06
NaF	0.06
Na_2CrO_4	0.05
Na_2SiO_3	0.04

* Adjusted to account for precipitation and filtration.

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

Table 23 lists the compositions of the contaminants found in the Savannah River Plant high-level waste tank supernate (volume, 380 million liters; density, 1.41 g/ml; pH, 14.5).

TABLE 23
COMPOSITION OF SAVANNAH RIVER HIGH-LEVEL WASTE TANK
SUPERNATE
(Results from Tank No. 2, F-Area)

CONTAMINANT	CONCENTRATION		QUANTITY	
	g/L	Bq/L	g	Bq
Sodium	214		8.13E10	
Nitrate	149		5.66E10	
Nitrite	133		5.05E10	
Hydroxide	76.5		2.91E10	
Aluminum	18.9		7.18E09	
Carbonate	<6.0		<2.28E09	
Phosphate	3.8		1.44E09	
Chloride	2.1		7.98E08	
Sulfate	1.9		7.22E08	
Chromium	0.2		7.60E07	
TOTAL	<605.4		2.30E11	
¹³⁷ Cs		1.3E11		4.9E19
¹³⁴ Cs		5.0E09		1.9E18
¹⁰⁶ Ru		2.3E09		8.7E17
⁹⁰ Sr		1.7E06		6.5E14
Gross alpha		<8.0E03		<3.0E12
TOTAL		<1.4E11		5.2E19

Source: *Evaluation of Nitrate Destruction Methods*, P.A. Taylor (Oak Ridge National Laboratory), D.E. Kurath and R. Guenther (Pacific Northwest Laboratories), DOE/MWIP-10, March 30, 1993. [Original source: R.S. Ondrejcin, *Chemical Compositions of Supernates Stored in SRP High-Level Waste Tanks*, DP-1347/UC-70, E.I. du Pont de Nemours & Co., Savannah River Laboratory, August, 1974.]

At SRP's DWPF, the sludge containing most of the radionuclides is separated from the supernate and salts. The sludge and radionuclides will then be immobilized and permanently interred in a repository still to be defined. The remaining supernate will be further decontaminated by ion exchange. Decontaminated supernate, along with the existing salts, may then have the status of LLW. This process might be applicable to the HLW stored at Hanford and WYNSC with minor mechanical technique modifications. The calcined material at ICPP is believed to be acceptable for immobilization in its present form. However, the possibility of separating the actinides from this material to reduce the amount requiring immobilization as high-activity waste is being investigated. Thus, a portion of the ICPP calcine could eventually be converted to low-activity waste also. An estimate of the DWPF low-activity waste product is presented in Table 24.

TABLE 24
CHEMICAL COMPOSITION OF DEFENSE WASTE PROCESSING
FACILITY SALT (DRY BASIS)

COMPOUND	WT. %
NaNO ₃	40
NaOH	19
NaNO ₂	14
NaAlO ₂	9
Na ₂ CO ₃	9
Na ₂ SO ₄	8
Miscellaneous	0.65
NaCl	0.2
Na ₂ C ₂ O ₄	0.1
Hg	0.05

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

Defense Waste Processing Facility Capabilities

The Defense Waste Processing Facility (DWPF) will solidify defense high-level radioactive waste at the Savannah River Site (SRS) for temporary on-site storage, transportation to, and disposal in a federal repository. The plant is scheduled to begin radioactive testing by December 1995, and processing of actual waste is expected to begin mid-1996.

Immobilization and confinement in a geologic repository of the hazardous radionuclides will ensure the long-term isolation of the waste from the environment and minimal maintenance and surveillance. This project will provide facilities that will perform the following operations:

- Transfer the treated HLW from waste storage tanks to feed tanks in the main processing building.
- Process the waste to produce canisters of waste immobilized in borosilicate glass.
- Store the filled containers on-site pending transfer to a waste repository.
- Solidify decontaminated salt for on-site disposal as industrial solid waste.

The DWPF project will provide facilities to immobilize the high-level waste in borosilicate glass in steel canisters. The canisters will be stored on the SRS until a federal repository is available. Decontaminated salt will be solidified as a monolith with low permeability for disposal on-site in concrete vaults as an industrial solid waste. The radioactive cesium separated from the salt will be combined with the sludge waste for vitrification.

The DWPF, which is expected to begin operation in 1996, will process the waste backlog inventory over approximately 20-25 years. The facility will be built near the H Chemical Separations Area and will include the waste processing facilities, waste storage vault, and power, service, and other support facilities.

The main process building will be seismic and tornado resistant and will include remotely operated and maintained process cells containing process vessels and equipment that will be

interconnected through systems of piping. The concrete walls will provide shielding against the highly radioactive waste solutions and solids. Cold feed chemicals and service systems, e.g., instrument connections, cooling water, steam, electrical power, etc., will be provided from adjacent areas behind the shielding walls to protect operating personnel. Ventilation air will be passed through a filter before final monitoring and discharge to the atmosphere. Also provided will be maintenance shops and areas, control rooms and similar service locations. New facilities and supporting services such as electrical substations, water wells, sanitary sewer systems, roads, shops and support facilities will be provided as needed.

This project will provide safe storage for six years' production of the radioactive waste glass in canisters. The storage facility will require minimum surveillance and attention. The waste form and storage will be compatible with transportation to, and storage in, a waste repository. If the waste repository is not available on a schedule to meet DWPF production output, additional storage capacity can be added.

CHAPTER 4. NITRATE-TREATMENT TECHNOLOGIES

Because the nitrates in the wastes discussed in Chapter 3 will normally increase the volume or reduce the integrity of all of the waste forms under consideration for final disposal, nitrate destruction before solidification of the waste is considered to be beneficial. For this reason, only nitrate-destruction technologies are discussed in this chapter.

According to the EPA, the Best Available Technologies for nitrate removal are ion exchange, reverse osmosis, and electrodialysis reversal (nitrate only). The only nitrate-destruction technology mentioned by the EPA in personal communications with KEI is bionitrification (AmRoTec Process), which is offered commercially by AP Technologies of Anchorage, AK.

TECHNOLOGY OVERVIEW

DOE has funded the development of several different nitrite-destruction technologies, which are being used or are currently under evaluation. Table 25 summarizes these processes and specifies the waste type to which each can be applied. There are techniques in use for destroying the nitrate radical if it is present as nitric acid, but the nitrate waste dealt with at most DOE defense facilities is as the nitrate salt, almost always sodium/potassium nitrate. The salt form is much more difficult to destroy than the acid.

Rocky Flats researchers set the screening criteria for a successful process demonstration at 90 per cent nitrate destruction with less than 500 ppm of NO_x in the process off-gas. Reduction in weight and volume of the waste form and immobilization of radionuclides were secondary objectives.

TABLE 25
NITRATE-TREATMENT PROCESS APPLICABILITY

METHOD	DILUTE NO_3 STREAM	CONCENTRATED NO_3 STREAM	NO_3 SALT
Thermal processes	---	---	X
Redox systems	X	X	---
Biological systems	X	---	---
Incorporation	---	---	X
Recovery	X	X	---

Source: *Commercial and Defense Nitrate Wastes and Processing Alternatives*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3282, DOE/TIC-4500 (Rev. 69), UC-70, Aug. 1982.

Table 26 provides an overview of the advantages and disadvantages of each technology that is being considered for nitrate destruction.

TABLE 26
NITRATE DESTRUCTION TECHNOLOGY OVERVIEW—
ADVANTAGES AND DISADVANTAGES

PROCESS	ADVANTAGES	DISADVANTAGES
ACIDIC AND ALKALINE WASTES		
Biocatalytic destruction	The use of enzymes enables very large specific catalytic activity to be obtained without the need for additional chemical reagents or the production of secondary waste streams. High selectivity allows it to be used to treat a wide range of compounds. Because potentials are low, no H_2 is produced. Immobilized enzymes are very stable. Electrodes have been stored dry for several weeks with no activity loss. Can treat highly concentrated or dilute solutions. Independent of pH so can be used to treat acidic or basic solutions.	Unknown due to immaturity of technology. Unoptimized system.
Hydrothermal Process	Organics present in waste used to destroy nitrate in both acidic and alkaline wastes. Generates no undesirable by-products, only nitrogen gas, carbon dioxide, and minerals. Possible to convert all of nitrate to nitrogen. Most of salts and some radionuclides and heavy metals may be removed as solid waste. If salts removed, liquid volume can be reduced by evaporation before final solidification.	Limited solubility of nitrates and other salts in supercritical water results in plugged reactor lines. High temperature and high pressure process requires exotic materials in reactor to prevent corrosion. Solidification of treated liquid and off-gas treatment for NO_x required.

TABLE 26 (CONT.)
NITRATE DESTRUCTION TECHNOLOGY OVERVIEW—
ADVANTAGES AND DISADVANTAGES

PROCESS	ADVANTAGES	DISADVANTAGES
ACIDIC AND ALKALINE WASTES (CONT.)		
Calcination		The off-gas must be treated to remove NO_x . High levels of nitrates increase ruthenium volatilization.
<i>Fluidized-bed</i>	In use around 30 years to solidify low-sodium wastes at INEL. Wastes with moderate sodium nitrate concentrations can be processed by careful blending with other waste streams.	Not feasible for alkaline wastes stored at Hanford, ORNL, and SRP. Inventories of sodium nitrate waste are accumulating at INEL due to the need to limit the concentration. Limits are required because sodium nitrate melts rather than decomposes at the calcining temperature. NO_x treatment is required if sugar is used to increase sodium concentrations.
<i>Plasma torch</i>	Sodium and potassium nitrates are converted to nitrogen gas and solid carbonates if a coke-filled furnace is used to convert oxides to carbonates.	The use of a coke-filled furnace makes the solids difficult to recover. If a coke-filled furnace is not used, sodium nitrate is converted to sodium oxide, which is very reactive and hygroscopic. Volatilization of radionuclides has not been determined.
Vitrification	Converts waste to a stabilized solid waste form. Large-scale facilities about ready to go on-line.	High energy and capital costs. Use with LLW having high sodium content needs to be proven with commercial melters. Liquid-fed systems (CFM, LFCM) have low throughput resulting in the need for larger-sized, more expensive systems. Safety/design implications of kerosene/oxygen (CFM) or feeding variable liquid waste onto molten glass (LFCM). Limitations on organic materials in the feed. Produces hot, contaminated, and corrosive off-gases that contain volatilized RCRA metals and radionuclides (esp. Cs, Tc), NO_x , SO_2 , and combustion gases. High levels of nitrates increase ruthenium volatilization. Volatilized radionuclides are expected to be

TABLE 26 (CONT.)
NITRATE DESTRUCTION TECHNOLOGY OVERVIEW—
ADVANTAGES AND DISADVANTAGES

PROCESS	ADVANTAGES	DISADVANTAGES
ACIDIC AND ALKALINE WASTES (CONT.)		
Vitrification (Cont.)		substantial (CFM) due to oxidizing, fluid conditions. This could compromise hands-on maintenance and operation. Generates spent melters that must be disposed. Contaminated ceramic refractory may provide an additional waste material for disposal.
<i>Minimum additive waste stabilization (MAWS)</i>	Consumes waste products as feed.	See Vitrification.
ALKALINE WASTE ONLY		
Biological denitrification	Nitrate is converted to nitrogen gas at ambient temperature and pressure. Equipment is simple, readily available, and easily operated. Some degradation of organics is expected.	Slow denitrification rate, which dictates large bioreactors. Bacteria have a low tolerance for sodium and require a narrow pH (7-8.5) and salt concentration range. Salt concentrations are limited due to osmotic pressure, which causes bacteria to swell and burst. Most of the stored wastes have high sodium concentration and require dilution prior to treatment. Certain metals can be toxic to bacteria cultures. Sludge requires treatment to stabilize or destroy the biomass to prevent off-gassing during storage. Large amounts of carbonate are formed as a secondary waste.
Electro-chemical reduction	Destroys nitrates without any chemical addition. Process can be used on alkaline wastes only. Competitive with other wet-processing approaches on the basis of power consumption. Can potentially simultaneously destroy organics. For dilute nitrate wastes, where an ion-exchange resin might	Other ions may plate out on the electrodes. Releases off-gases: NH ₃ , N ₂ O, and NO ₂ . Hydrogen generation at the cathode presents an explosion hazard. Process requires significant quantities of make-up water. Produces 40 pounds of NaOH, which must be disposed, for every 85 pounds

be used in the EIX process, resin requires no regeneration.

NaNO₃ converted. Chromium concentrations above 1 mg/L significantly reduce electrical efficiency. Uncontrolled electro-osmosis can lead to volume imbalances. Treated solutions require solidification for final disposal, potentially increasing volume by 40% or more.

Nitrate to Ammonia and Ceramic or Glass (NAC/NAG/NAX)

Low temperature (50°C) and atmospheric pressure reaction with aluminum. Low temperature prevents formation of combustion products such as NO_x. Generates uncontaminated ammonia, which can be destroyed or reused. Immobilizes many inorganic contaminants such as PO₄, SO₄, Cl, F, Cr, Al, Cs, Tc, and ⁹⁰Sr. The alkaline waste solutions stored at Hanford, ORNL, and SRP may not require any pretreatment prior to nitrate destruction. Reaction product can be converted to a glass (NAG) or ceramic (NAC) or it can potentially be mixed with another reagent (i.e., lime) to produce final waste form (NAX) eliminating thermal processing as required for NAC and NAG.

Off-gas system needed to handle ammonia. Highly exothermic reaction requires safety controls. An inert gas (N₂) is used to dilute hydrogen, which only forms below about 5-10 g/l NO₃. Actual plant may not require inert gas. Reaction product is not considered to be a stable final waste form and must be stabilized by vitrification or sintering. The stabilized solid waste form generated by the process has not yet been qualified as acceptable for final disposal, although it is expected to qualify.

NAC

Mixture of phases believed to be tolerant of composition variability. No vitrifier required and no major secondary wastes is generated. Reducing conditions promise little volatility of radionuclides. Initial indications of excellent leach performance. Produces an insoluble waste form with a significant reduction in volume (70% for a 4 M nitrate waste).

May be difficult to sinter large volumes of reaction product.

TABLE 26 (CONT.)
NITRATE DESTRUCTION TECHNOLOGY OVERVIEW—
ADVANTAGES AND DISADVANTAGES

PROCESS	ADVANTAGES	DISADVANTAGES
ALKALINE WASTE ONLY (CONT.)		
<i>NAG</i>	Glass is more dilute and more accommodating of feed variabilities. Avoids calcination and has different glass composition. Avoids combustible/explosive mixtures and liquid feeds. Expect volatilization of radionuclides to be no worse than LFCM. Al/Si glass expected to be more leach resistant than borosilicate glass. Produces an insoluble waste form with a significant reduction in volume (70% for a 4 M nitrate waste).	Glasses have relatively high viscosity. Higher process temperatures are required for flowable product during vitrification. Adding fluxing agents to reduce process temperature lowers waste loading. Additions of B ₂ O ₃ lowered viscosities but some phase separations were observed. NAG results in a larger volume of waste to dispose because of the need to add silica during the glass-forming step.
<i>NAX</i>	Non-thermal treatment and no off-gasses to treat.	Untested process. NAX is expected to result in even larger volumes of waste to dispose than NAG. The use of lime as the reactant is not expected to tie up sodium and other elements as does NAC and NAG.
Solidification (i.e., grouting)	Widely used technology.	Large volume increases (40% or more). Handles limited levels of caustic, sulfate, nitrate, and halogen.
ACIDIC WASTE ONLY		
Chemical reduction	Used for many years in full-scale facilities on acidic HLW.	Converts nitrates to nitrogen oxides, which require off-gas treatment. Unstable process that requires safety controls. Explosive reaction reported by Savannah River. Not capable of destroying all of the nitrate so substantial concentrations of nitrate would be present after treatment. Treated waste requires solidification, potentially increasing waste volume.

Source: KEI

DESTRUCTION METHODS

According to *Evaluation of Nitrate Destruction Methods* (DOE/MWIP-10, March 1993), three processes have been used to treat high nitrate-concentration wastes at full-scale facilities: biological denitrification, calcining, and chemical reduction. Two full-scale vitrification plants are currently under construction.

The study referenced above indicated that three technologies appear to merit further development. The *nitrate to ammonia and ceramic* process produces an insoluble waste form with a significant volume reduction, *electrochemical reduction* destroys nitrates without any chemical addition, and the *hydrothermal process* can simultaneously treat nitrates and organics in both acidic and alkaline wastes. These three technologies have been tested using lab-scale equipment and surrogate solutions. At their current state of development, it is not possible to predict which process will be the most beneficial for a particular waste stream.

[Note that high levels of nitrates increase ruthenium volatilization during any high-temperature processing of the waste, such as calcination or vitrification. NO_x generation is also an issue with several of these technologies, particularly with the high-temperature processes.]

CHEMICAL PROCESSES

A variety of chemical agents and procedures were tested by RFP researchers in preliminary experiments to scan a wide range of potential methods for processing acidic aqueous nitrate wastes. The materials tested were categorized in the following groups:

- Reducing agents—chemical agents that might destroy the nitrate radical (NO₃⁻) by reducing the nitrate nitrogen to its elemental form (e.g., urea, formic acid, formaldehyde, ascorbic acid, sulfamic acid, and sucrose).
- Reaction promoters—chemical agents that might convert nitrate compounds to nitric acid, which could be more susceptible to the effect of a reducing agent (e.g., potassium bisulfate, sulfuric acid, phosphoric acid).
- Catalysts—materials that could enhance the nitrate destruction process without directly entering the chemical reaction (e.g., copper, zinc, platinum, nickel, rhodium, iron oxide, aluminum oxide, aluminosilicate).

Reduction

Chemical reduction has been used in Europe and Japan to treat acidic high-level wastes for many years. The process will not normally destroy all the nitrate in the waste and will not work in alkaline solutions. As a result, the chemical reduction process has not been tested on the alkaline mixed wastes stored at DOE facilities. Unless methods are developed to use the process under alkaline conditions, large amounts of acid would be required for pH adjustment before treatment. The treated solution would require solidification before final disposal. Costs for building and operating a chemical reduction facility are expected to be similar to those for the NAC process facility.

A wide range of reducing agents, such as formic acid, formaldehyde, sugar, and ammonia, can be used to convert nitrate to a mixture of nitrogen gas and NO_x. Also refer to the section discussion "Organic Reduction in Acid" later in this section. Chemical methods for

nitrate destruction can usually be carried out at ambient or slightly elevated temperatures. The nitrate ion is a strong oxidizer and with some reducing agents there is a definite explosion hazard. Selection of the correct reductant would also be dependent on its cost and availability, as a relatively large amount would be required.

Rocky Flats Testing

A large number of possible reactions have been tested for the reduction of nitrates, present as the salt, in aqueous solutions. While some of the tests were limited in scope and no attempt was made to optimize the nitrate reduction, the end result was that even a twofold increase in nitrate reduction would rule out most aqueous reactions as a possible production candidate.

Chemical Evaluations

Ascorbic acid ($C_6H_8O_6$) reacted with $NaNO_3$ only after the formation of a carbon char as the mixture reached semi-dryness. The ensuing reaction achieved 95 per cent denitrification but was violent and uncontrollable under the test conditions.

Sucrose ($C_{12}H_{22}O_{11}$) achieved an average of only 8 per cent denitrification. It also formed a carbon char that reacted violently with $NaNO_3$.

Formaldehyde ($HCHO$) produced an average of only 7.5 per cent denitrification under the test conditions. The denitration of high-level waste (HLW) using formaldehyde has been performed for many years at the Marcoule and La Hague plants in France and at the Tokai-Mura plant in Japan. Formaldehyde is metered into a boiling solution of HLW at a controlled rate. Because the process is used mainly to adjust the acidity and nitrate concentration of the HLW prior to extraction processes, destroying all the nitrate is not a goal of these facilities.

There is normally an induction period after the formaldehyde is added to the HLW before the reaction initiates. If excessive amounts of formaldehyde build up in the solution before the reaction starts, rapid reaction rates could produce high pressures in the reaction vessel. Several incidents of this type have occurred in the full-scale facilities with minor consequences. There is also the possibility of unstable oscillatory reaction, caused by periodic buildup of reactants followed by very rapid reaction, occurring if noble metals, such as palladium, are present in the waste solution.

The off-gas will contain high concentrations of NO_x and treatment will normally be required. The gas could be scrubbed, but this will produce large volumes of radioactively contaminated nitric acid or nitrate salts that will require further treatment for disposal. The preferred treatment for the off-gas would be catalytic reduction with ammonia, which will produce nitrogen gas.

Potassium bisulfate ($KHSO_4$), sulfuric (H_2SO_4), and phosphoric acid (H_3PO_4) all appeared to improve denitrification, but more comprehensive testing was needed to evaluate each promoter with the more promising reducing agents.

Sulfamic acid (NH_2SO_3H) achieved 97 per cent removal of nitrates, but it was determined that a large percentage of the NO_3^- was being converted to HNO_3 rather than being destroyed.

Formic acid (HCOOH) achieved the best denitrification results of any reducing agent tested. Efficiencies ranging from 13 to 85% were observed in tests with various promoters and catalytic materials. Examples of the reactions that can occur with formic acid are shown below:

Conclusions

The following are some general conclusions that were drawn by the Rocky Flats Plant researchers:

- The aqueous denitrification by a urea-nitrate reaction does not appear to be a practical process for the most prevalent waste forms in LLW streams.
- Use of reaction promoters and nickel catalyst greatly increased the denitrification efficiency of the reducing agents tested. However, the concurrent increase in cost and process complexity for the tested reactions does not seem practical for a large-scale process.
- Aqueous denitrification reactions result in a net weight increase over the starting nitrate waste.
- Aqueous denitrification can be accomplished using a two-step method, but the final sulfate waste product will show a net increase in weight over the starting nitrate waste. Peak NO_x emissions are above the 500-ppm screening level desired for a production process.
- No aqueous denitrification procedure has produced results equal to those achieved by thermal methods tested during this project.

Electrochemical Destruction

Electrochemical methods for destroying nitrates, nitrites, and organic compounds in high- and low-level waste are being evaluated. Much of the development work in the U.S. has been done at the Savannah River Laboratory. Others involved are Bradtec, Inc. (Bristol, United Kingdom) and AEA Industrial Technology (Oxfordshire, United Kingdom).

In an electrochemical cell, nitrate and nitrite can be reduced to nitrous oxide, nitrogen, and ammonia. These gases have very low solubilities in alkaline solutions and are effectively separated from the waste. Metal ions can be reduced producing solid phases or deposits on the electrodes, which can once again be removed. In addition to electrochemical reduction, the corresponding electrochemical oxidation reactions can be brought about to oxidize organics to carbon dioxide and water.

Research is being undertaken to examine divided parallel-plate, packed bed, and fluidized-bed electrochemical cells, and identification of electrocatalysts for these destruction reactions. A number of different electrolytic cell configurations exist and, depending upon the cell, can produce a mixture of gases such as NH₃, N₂, O₂, and H₂.

An overall reaction that might represent both anodic and cathodic reactions in an electrolytic cell is as follows:

Bradtec's electrochemical ion-exchange (EIX) process consists of the separation of the nitrate from the waste stream by an anion-exchange resin followed by migration of the nitrate anions to an anode. The nitrate can be recovered as nitric acid, or it can be destroyed in an electrochemical cell to produce nitrogen and other products, thus reducing the volume of the waste stream. Bradtec indicates that power requirements are relatively low at 0.96 kWh/gmole of nitrate destroyed or a total of 1.6 kWh/gmole for both separation by EIX and destruction. Such power consumption at \$0.03/kWh would result in power costs of \$0.46/kg nitrate.

Electrochemical methods of reducing the amount of nitrate and nitrite in mixed waste at SRP have been investigated for several years using single- and multiple-cell electrolysis compartments. Investigations on SRP wastes indicate that electrolysis is a viable means of destroying nitrates and nitrites. Research indicates that the efficiency of the reduction of nitrates and nitrites depends on the current density, presence of chromate ion, temperature, and electrode spacing.

The presence of chromium in the waste solution can reduce the electrical efficiency of the process because of the cyclic oxidation and reduction. The electrical efficiency can be reduced from > 90 per cent to < 40 per cent by 16 mg/L chromium. For aqueous wastes with dilute concentrations of nitrates, destruction can be facilitated by concentration of the nitrates. One approach to concentration involves the EIX process that combines ion exchange and electrodialysis with destruction.

Such cells are subject to a number of problems:

- All of these cells produce 40 kg of sodium hydroxide for every 85 kg of sodium nitrate processed. However, considerable reduction (possibly up to 75%) in the volume of waste requiring disposal could be realized by recovery and recycle of the sodium hydroxide produced. The NaOH formed is not a good candidate for grout. It must be diluted first, increasing the waste volume even further.
- In-cell crystallization of salts, due to evaporating liquid, foul electrodes and lower current efficiency. Criticality issues may become a concern with Hanford wastes.
- Trace amounts of chromium (<36 ppm) can drop cell efficiency from the high nineties down to the thirties due to cyclic oxidation and reduction of chromium in such cells; the result is that decomposition times may quadruple. [The NAC process is unaffected by chromium because this species can form a highly insoluble aluminate.]
- Many metals and some radioelements plate out on electrode surfaces and lower cell efficiency.
- The electrolytic process does not bring with it the potential for producing its own waste form and the associated chemistry that makes alumina-silica such a good host matrix.

In-situ Redox Systems

Taking advantage of the nitrate ion's strong oxidizing power would provide the most direct and perhaps most efficient method of chemical disposal. The basic mechanism involves introducing an easily oxidized substance (a reducing agent such as urea) into a nitrate waste stream (dry or reslurried salt) and optimizing reaction conditions. The nitrate is reduced to N_2 , O_2 , or CO_2 and a resultant residue, usually a carbonate. Tests have been conducted on both synthetic and actual nitrate wastes using several different reducing agents. The dried residue in all cases show significantly reduced (in many cases essentially zero) residual nitrate concentrations. This approach appears to be applicable for on-stream processing and would be applicable to stored wastes. [Note: The authors of *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies* indicate that laboratory tests conducted at Rocky Flats Plant showed that urea was not efficient in the destruction of simulated LLW nitrate under the test condition.]

Biological Processes

Biocatalytic Destruction

A compact enzyme-based reactor system is being developed for the reduction of nitrate and nitrite to N_2 and H_2O in aqueous mixed waste and low-level radioactive waste. The project will demonstrate the validity of using immobilized enzymes coupled with biphasic partitioning to efficiently destroy nitrate and nitrite. The reducing equivalents are provided by a low-voltage electrical current, which transfers electrons from the cathode to the enzymes via an electron transfer dye. The biphasic system is necessary to protect the enzymes from excessive concentrations of electrolytes, especially H^+ and OH^- . Excessive concentrations would result in enzyme inactivation while simultaneously allowing the transfer of nitrate and nitrite from the waste stream to the catalytic chamber. The use of enzymes enables very large specific catalytic activity to be obtained without the need for additional chemical reagents or the production of secondary waste streams.

Biological Denitrification (Biodenitrification)

Biological denitrification is included in the chemical section as it involves an organic reductant, in this case bacteria. Many types of common bacteria, under anaerobic conditions, can convert nitrates and nitrites to molecular nitrogen and oxygen. Basically, this is a variant form of their inherent metabolism as it also requires a stoichiometric carbon source. Several pilot operations have been conducted at DOE facilities. However, because the carbon is oxidized to carbonate, sodium carbonate is formed in large amounts creating a secondary waste to dispose.

Biodenitrification separates metals by a combination of biosorption (adsorption onto bacteria) and precipitation. Some degradation of organics is also anticipated. The process uses a mixed culture of natural bacteria isolated from the Great Salt Lake and Death Valley area. These bacteria are able to grow and reduce nitrate in the very high salt concentrations found in the tank wastes. However, it is limited due to osmotic pressure that causes the bacteria to swell and burst (lyse).

The bacteria are grown in a bioreactor and then recycled to a biosorption tank where they are mixed with the incoming waste. The high radioactivity and metals concentration in this tank may kill the bacteria, but dead bacteria biosorb metals equally well.

The bacteria and any chemical precipitates that may have formed are removed by filtration, generating a biomass sludge waste containing the metals and radioactivity. In most cases, this sludge will be a low-level radioactive waste, and will be dried and sent for final disposal by grouting or vitrification. The liquid containing the nitrate, organics, and very low levels of metals flows into the bioreactor.

Use at DOE

Biodenitrification has been used at the Oak Ridge Y-12 Plant since 1976 to treat highly concentrated nitrate wastes. It is used to treat wastes containing high concentrations of aluminum nitrate and nitric acid. Wastes with high sodium concentrations, which include most of the stored wastes, require neutralization and significant dilution before biodenitrification is possible. The Y-12 Plant uses calcium acetate as the carbon source and generates large quantities of calcium carbonate solids to be disposed.

The Y-12 wastes contain low concentrations of uranium, but they do not contain fission products like most of the currently stored mixed wastes. More dilute waste streams are treated in fluidized-bed bioreactors at the Portsmouth Gaseous Diffusion Plant and the Fernald Feed Materials Plant. The process has been tested on the high sodium-nitrate concentration mixed wastes that are stored at DOE facilities with unsuccessful results.

Process Parameters

A readily biodegradable organic carbon source (sodium acetate, calcium acetate, alcohol) supplied to the bacteria converts the nitrate to nitrogen gas and carbon dioxide. Moderate temperatures (15 to 50°C) and pH (7.5 to 8.5) must be maintained in the bioreactor for optimal denitrification rates and anaerobic conditions are the most efficient mode for bioreactor operation. The acetate carbon source is oxidized to carbon dioxide while reducing nitrate. A phosphate-containing salt for intercellular energy transfer and storage must be added, producing larger volumes of carbonate salt sludge that contains calcium or sodium carbonate, aluminum hydroxide, and biomass. The nitrogen is released to the atmosphere after being filtered and the sludge must be disposed.

Any remaining metals adsorb onto the growing bacteria, but their concentration is now too low to inhibit bacterial metabolism. The effluent from the bioreactor, after filtration, is a concentrated solution of non-radioactive, non-hazardous salts in which nitrate has been replaced mainly by bicarbonate.

The feed stream to the Y-12 bioreactors contains about 5 M total nitrate (mostly aluminum nitrate) and about 1.5 M nitric acid. The bioreactors can treat about 2 grams of nitrate per liter of reactor volume per day (2 g $\text{NO}_3^-/\text{L}/\text{d}$). The denitrification reaction produces enough alkalinity to neutralize the feed and maintain a pH of about 7.5 in the bioreactor as long as the feed solution contains less than 1.5 M free nitric acid.

Feeding highly concentrated nitrate wastes to a bioreactor is feasible only if the cations in the waste will precipitate in the bioreactor. For soluble cations, such as sodium, the concentration of the waste stream fed to the bioreactor is limited by the tolerance of the bacteria for the cation. In the case of sodium, high denitrification rates have been observed at sodium concentrations up to 1.2 M. It may be possible to isolate or develop bacterial strains that could tolerate even higher sodium concentrations. Acute radiation experiments have demonstrated that 0.3 rad/s should not adversely affect the denitrification bacteria.

Perhaps the most significant operational parameters that should be considered is the degree of nitrate loading on this type of system. Since it is metabolically driven, the degree of loading is limited (~10,000 ppm) and throughput time versus system size become significant. Considering process application, economics and system design, this method of nitrate treatment would probably be best suited as a pre-discharge final polishing step to meet pending EPA discharge limits.

Nitrate to Ammonia and Ceramic/Glass (NAC/NAG/NAX)

The Nitrate to Ammonia and Ceramic/Glass processes are new technologies being developed at Oak Ridge National Laboratory (ORNL) that involve chemical reduction of the nitrate contained in the mixed (hazardous and radioactive) tank waste to gaseous ammonia. The NAC/NAG/NAX process can achieve concentrations of nitrate below drinking water standards. Benchtop studies using Hanford single-shell tank (SST) simulants and actual ORNL Low Level Waste have conclusively shown that between 85 and 99 per cent of the nitrate can be readily converted to gaseous ammonia.

Other benefits are low temperature solidification process (50-90°C as compared to 1100°C with vitrification) and a final waste volume reduction of 55 to 75 volume per cent (as compared to a 30 to 40 per cent increase by grouting. In addition, the NAC/NAG/NAX process also precipitates most cations, including strontium, from solution forming "highly" insoluble aluminates.

The higher ratio of positive charge to ionic radius of the cation, the more insoluble is the resulting material. This means that metal ions with a +3 charge such as chromium would be more insoluble than calcium. This means that many metal and non-metal cations will enter the dense, solid ceramic matrix as a very insoluble mineral. Unfortunately, because the sodium and the alkali metals do not appreciably react to form these insoluble materials, silica must be added to immobilizing the mobile alkali metal component.

Reaction with Aluminum

In this process, aluminum powders or shot or radioactively contaminated scrap aluminum can be used to convert alkaline, nitrate-based supernate to ammonia and an aluminum oxide-sodium aluminate-based solid. The reaction is exothermic and requires cooling to control the reactor temperature to between 50 and 60°C. Experiments using an ethylene-cooled reactor have been successfully performed. Results show that the reactor temperature can be easily controlled. [Note: Nitrite, which is also present in some of the DOE waste, requires less aluminum than does nitrate.]

In the NAC/NAG/NAX processes, aluminum powder or shot is used to convert radioactive alkaline, nitrate-based supernate to ammonia and a stable alumina-silica-based ceramic or glass solid. The NAC/NAG/NAX process is actually the Hall-Herault process in reverse; the Hall-Herault electrochemical process is used today to produce aluminum. The major difference between NAC/NAG/NAX and the Hall-Herault processes is that NAC/NAG/NAX occurs in an alkaline, aqueous solution rather than in a water-free molten salt bath.

Upon addition of aluminum to solutions that are sufficiently alkaline, there is a delay in reactivity due to the presence of the protective oxide coating. The delay is accompanied by the absence of an expected rise in solution temperature since the reaction is so highly exothermic (381 kcal/mole of sodium nitrate). After several minutes at, for example 50°C and pH 12, a marked rise in temperature is observed, accompanied by the evolution of

ammonia gas. The delay is most pronounced during start up of the reactor and becomes shorter with time after each successive addition of metal. The oxide coating is partially broken down following metal addition and the reaction accelerates. Factors that can accelerate the reaction of metal with the solution and its electrolyte are:

- High shear mixing, which can cause the oxide surfaces to be abraded,
- Both a high pH and high temperatures, which favor a faster reaction,
- The presence of increasing amounts of highly abrasive Gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, also known as Hydrargillite) that functions as a seed in the reaction, which can remove the oxide coating, and
- The physical configuration of the reactor such as the presence of baffles or its shape, which can abrade oxide coatings and expose bare metal to solution faster.

Theoretical Quantity

In the NAC/NAG/NAX processes, the aluminum metal can be considered to be like a charged capacitor or battery, ready to release its energy during the reduction of nitrate to ammonia gas. Theoretically, 0.85 kg of metal per kilogram of sodium nitrate (2.67 moles of aluminum for each mole of sodium nitrate) are required to reduce all of the nitrate in the supernate. This reaction is shown by the equation below.

When using the theoretical amount of aluminum to reduce nitrate to ammonia and a silica to total sodium molar ratio of 1.5:1, a sintering temperature of 1,225°C is required. At this temperature, reactor solids quickly densify to an approximate density of 2.8 g/cc.

Experimentally Determined Quantity

Experiments show that excess aluminum must be added to reduce the nitrate to low concentrations. When operated on a semi-continuous basis, the actual aluminum used to produce a 1,000 mg/L nitrate residual from a 3 to 4 M solution is approximately 110 per cent or 0.94 kg aluminum per kilogram of sodium nitrate (2.96 moles of aluminum for each mole of sodium nitrate) of the theoretical requirement to reduce all the nitrate. This results in a nitrate conversion of around 99.5 per cent.

The excess aluminum reduces the hydrogen component of water to hydrogen gas. Batch tests have shown that some hydrogen is produced when the aluminum is first added to the reactor before any gibbsite has formed. However, most of the hydrogen is produced at the end of the reaction when the nitrate concentration is low in comparison with the concentration of water. Tests are being conducted at a bench scale using a continuous stirred tank reactor (CSTR) to refine the process and determine operating condition necessary to reduce the required excess aluminum and to reduce or eliminate the hydrogen gas produced. Based on work to date, these conditions seem to be: 1) at least a 1,000 mg/L residual nitrate concentration, 2) enough liquid to provide efficient mixing, and 3) a solution saturated with respect to aluminate. Experimental data to date, based on the above operating conditions and 10 per cent excess aluminum, yields the following stoichiometric equation for the process.

Reaction Product

The solid product from the reaction of aluminum metal with a 50°C alkaline ($\text{pH} > 11.5$) solution of sodium nitrate is a sand-like precipitate. After oven drying, analytical results indicate the material is gibbsite (96%) with a small percentage (3-4%) of sodium aluminate and a trace amount of caustic. **Note:** If the precipitate is allowed to stand in the reactor for a number of hours, it will harden to a cake that can only be dissolved, with some difficulty, with boiling sodium hydroxide solution. In tests with Tc in low nitrate solutions and in Hanford salt cake simulants, 99 per cent reported to the solid phase when the reaction took place in a reducing atmosphere.

Role of Silica

The presence of sodium, which is produced by the reduction of sodium nitrate, tends to make ceramics and glasses leachable. This is an undesirable characteristic in a final waste form.

To solve this problem, silica (40 μm quartz) is added to the reactor to bind the sodium, potassium, or cesium, if present, in a nepheline phase ($\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) of the final structure. Typical compositions reported in the literature are 8 per cent Na_2O , 15 per cent Al_2O_3 , and 67 per cent SiO_2 . Increasing silica in the NAC reactor produces a flowable glass that can be processed in a vitrifier.

Silica also binds most metals and non-metals in the ceramic during sintering or the glass during vitrification. The quantity of silica added is based upon the total sodium in the waste and whether the material is to be a glass, ceramic, or a glass ceramic. The researchers indicate that they have the flexibility to produce any of these material types. Refer to Tables 27 and 28, which present the leach results for varying compositions.

Figure 1 shows the NAC/NAG/NAX process product options. Silica is added as a feed to the reactor vessel for glasses, ceramics, and glass ceramics, but additional silica is added to the reaction product prior to forming a glass or glass ceramic. No additional silica is added if the final form is to be a ceramic, which is formed simply by heating (i.e., sintering) the reaction product. If silica is added to the reaction product and sintered, a glass-ceramic material results that is typically composed of 62-70 per cent silica, 17-22 per cent alumina, and 3-5 per cent sodium or lithium oxide. If silica and B_2O_3 or other flux is added to the reaction product and heated, a glass results. Alkaline oxide fluxing agents such as boron oxide, calcium oxide, or magnesium oxide are sometimes added to improve the glass processing parameters such as melt temperature and viscosity. A typical soda-lime-silica glass contains 70-74 per cent silica, 0.5-4.5 per cent alumina, 5-16 per cent lime, and a fluxing agent.

At the present time, 150 per cent of the theoretical quantity of silica required to form a nepheline product is added to the reactor. This ceramic product currently contains approximately 50 per cent SiO_2 , 30 per cent Al_2O_3 , and 18 per cent Na_2O . In some of the ORNL work, enough silica has been added to the reactor feed to form a ceramic compound containing a sodium-silica-alumina ratio of 1:1:1 when the reactor product is sintered.

[**Note:** Researchers at Rocky Flats have demonstrated the feasibility of using waste raschig rings as the glass source for treating sludge waste.]

Fig. 1. NAC Process Product Options

ORNL DWG 93A-839R

NAC Process Product Options

DRAFT

Final Waste Form

The final, nearly nitrate-free ceramic-like precipitate can be processed in three ways: 1) dry, calcine, press, and sinter like other ceramics, 2) add more silica and a fluxing agent to form a glass or glass-ceramic, or 3) grouting (a recently proposed alternative). Conceptually, it is possible that an additive such as lime, $\text{Ca}(\text{OH})_2$, can be added to the alumina-silica-based discharge from the reactor and, following pressing and low-temperature heating, be converted to an acceptable waste form.

Based upon the starting volumes of 6.2 and 3.1 molar sodium nitrate solution (probable supernate concentrations resulting from salt-cake/sludge removal from the Hanford SSTs, volume reductions of 50 to 70 per cent were obtained for the waste form produced. Since the co-produced ceramic or glass can function as its own waste form, it offers savings associated from both having a smaller volume of waste form and from eliminating other process steps such as grouting.

Reaction Product

At one time, it was thought that the reaction product might be a suitable final waste form because the unsintered product from the reactor binds metals. However, it was determined through leach tests that this form is unacceptable because of the mobility of the sodium ion. The sodium content and molecular speciation in the product solid are addressed by adding crystalline silica to form the mineral nepheline in the sintered or vitrified product. At a minimum, one mole of silica for each mole of sodium that is present in the initial waste will be required to bind sodium in this phase.

Ceramic

In the NAC process, the final nitrate-free ceramic product is calcined, pressed, and sintered like any other ceramic. The sand-like reaction product is dried and then calcined at between 600 and 800°C to produce different types of alumina (α -, β -, γ -alumina) with different properties. Each of the higher forms of alumina becomes successively more chemically inert following calcination and sintering (gibbsite—stable below 155°C, boehmite—stable below 280°C, corundum—melts at 2,020°C). In addition, higher temperature sintering of alumina causes fusion to occur between the particles where contact between them is made, thereby increasing the physical strength and increasing the density of the form.

In small-scale tests, the powder was uniaxially pressed at 69 Mpa (10,000 psi) and microwave sintered in the range of 1,300 to 1,400°C (28-Ghz range). The ceramic produced by this process contains nepheline and mullite fused to alumina particles. The material has a density of approximately 2.6 g/cm³ and consists of submicron particles that produce a solid with much smaller pores than cement-based solids. This prevents water from penetrating as it can with cement-based grout or even with high-grade structural concrete. Small pores also inhibit the ability of ions to diffuse into or out of such a ceramic product without water.

It is expected that, in a large-scale production facility, the pressing step will be eliminated and the calcining and sintering step will occur simultaneously in a cement-mixer-type kiln. Instead of a solid ceramic product, the final waste form will be pea- to marble-size clinker having a bulk density of 1.95 g/cm³.

Sintered pellets produced from Melton Valley Storage Tank supernate have been leached in accordance with the NRC's American Nuclear Society (ANS) 16.1 leach test for the radioelements ^{85}Sr and ^{137}Cs . Despite lengthy counting times, ^{85}Sr could not be detected in the leachates and ^{137}Cs was only slightly above background and corresponded to a leach index of 11 to 13, comparable to that expected from glass forms. Leach testing of unsintered reactor product spiked with eight hazardous metals of interest to the EPA proved that even unsintered product can pass the TCLP test.

Glass and Glass Ceramic

Adding silica above the amount necessary to form nepheline produces a glassy phase that qualifies the ceramic as a "glassy" ceramic. According to Terry Tiegs (ORNL, Metals and Ceramics Div.), the amount of silica required for the NAG process is three to four times higher than for the NAC process.

The excess added quartz forms a glass that serves to bind together crystalline grains. Most ceramics do not consist of a single crystal but are composed of numerous crystals joined to form polycrystalline structures. Most of the ceramics produced are mixtures of crystalline grains and a glassy phase that frequently acts as the bond.

It is expected that some sodium associated with the sodium aluminate may also dissolve in the glass as oxide, as would the aluminum associated with this salt. This dissolution into the excess glassy phase can only be made through the respective oxides of sodium and aluminum for only oxides are soluble in glasses up to their solubility limits in this medium.

At the high temperatures associated with sintering it is expected that excess glass will become a solvent for oxides of sodium and aluminum. In addition, excess silica also serves to further lower the fusion point of the alumina-silica-sodium oxide-based ceramic form as do the presence of ionic salts associated with the waste solution.

Ammonia Generation

The NAC/NAG/NAX process produces large quantities of ammonia upon reducing nitrate, which passes through nitrite on its way to ammonia. Any nitrite that is present would also produce ammonia. It is possible that a small amount of hydrogen will also be generated.

Present plans for pilot-plant scaleup include recovery and disposal of ammonia by scrubbing the ammonia into dilute sulfuric acid to form the salt, ammonium sulfate. Many options are available for handling the ammonia off-gas using "off-the-shelf" technologies, which include the following:

- Scrub into dilute acid to form ammonium salts,
- Cool and pressurize into liquid ammonia for reuse,
- Convert to nitrogen and water vapor in a heated catalytic-bed tower, and
- Re-oxidize to form nitric acid for reuse on site.

The researchers indicate that the best option for on-site treatment at Hanford might be catalytic conversion. This method is recommended because it does not create a secondary, aqueous-waste stream that would require storage and treatment.

The conversion of gaseous ammonia to nitrogen and water vapor is a standard, two-step commercial operation that first uses an oxidative step to form NO_x by reaction with air and then reduction with a slip stream of ammonia to nitrogen and water vapor. In this process, air is mixed with the ammonia and preheated to 315°C and then passed over a vanadium oxide-titanium oxide catalyst bed that heats to 650°C due to the heat of oxidation. The NO_x formed at 95 to 99 per cent efficiency is again preheated to 315°C and passed over a similar reductive catalyst that heats to 427°C due to the reaction heat, forming nitrogen and water vapor at a 95 per cent efficiency.

Efficiency and Volume Reduction

It has been shown in bench-top batch feasibility studies with Hanford single-shell tank (SST) simulants that between 90 and 99 per cent of the nitrate at Hanford is readily converted to ammonia by the NAC/NAG/NAX process. The converted percentage is primarily dependent upon the ability of the mixing system in the reactor to stir the solid/liquid slurry when the batch mode is used. If the process is run in the continuous mode, high concentrations of nitrate can be treated at still higher overall efficiencies.

The overall efficiency of the use of aluminum metal reactant has been increased from 50 to 91 per cent by operating in the continuous mode. The ORNL researchers estimate that this operation mode will reduce processing costs by decreasing the amount of aluminum, a costly reactant, down to an estimated \$2/kg of nitrate converted. It will also operate with waste solution feeds containing nitrate at near saturation. Use of DOE radioactive scrap aluminum from around the U.S. will eliminate the need for decontamination, thereby lowering DOE decommissioning and decontamination (D&D) costs.

Volume reductions as high as 70 per cent have been obtained with starting volumes of 6.2 and 3.1 molar sodium nitrate solution. These are the probable supernate concentrations resulting from salt-cake/sludge removal from the Hanford SSTs. This volume reduction compares with an expected 35 to 50 per cent volume increase if the grouting technique were used.

Leaching Results

Table 27 presents the results of the sodium cation leach test for the waste produced by the NAC/NAX process. Table 28 presents the results of leaching tests with RCRA metals. Sodium leachability as per NRC ANS 16.1 procedure yielded leach index of 16 for the sintered product. NAC reactor product (with and without further thermal processing) passed the TCLP leach tests when feed contained higher levels of heavy metals. ANS 16.1 leach of NAC product using MVST supernate had a ^{137}Cs leach index of 16. The following were not detected: ^{85}Sr , ^{60}Co , ^{57}Co , ^{65}Zn . Good leach results from inferior product made during scoping studies indicate that optimized NAC waste should easily pass WAC for low-level disposal.

TABLE 27
NAC SODIUM CATION LEACHING TEST

Si/Na Ratio	Na Leached (%)	
	Al:Na Ratio = 8/3:1	Al:Na Ratio = 16/3:1
0.5:1	14.71	12.09
1:1	0.28	0.50
1.5:1	0.02	0.05

* 90-day test in deionized water

Source: NAC researchers (ORNL)

TABLE 28
RCRA METALS TCLP LEACHING TEST RESULTS FOR NAC WASTE

SPECIES	LIMIT	UNSINTERED (PPM)	SINTERED
Ag	5	0.59	0.017
Ba	100	35	1.8
Cd	1	0.067	0.010
Cr	5	0.024	0.093
Ni	*	*	0.047
Pb	5	0.73	0.11
Hg	0.2	0.032	**
Se	1	0.20	**
As	5	0.44	**

* Expected future addition to TCLP test.

** Not present due to expected volatility.

Source: NAC researchers (ORNL)

Scrap Aluminum Consumption

One of the benefits of the NAC/NAG/NAX processes over immobilization techniques such as grouting and vitrification is that contaminated aluminum scrap metal from DOE sites can be consumed in the process. Present indications are that on-site burial of the scrap metals as low-level-radioactive wastes will not be acceptable, both from a technical standpoint (wet-climate geological limitations) and public acceptance. Off-site disposal in a western dry-climate location might conceivably be an alternative but would create other serious problems associated with shipping large quantities of radioactively contaminated materials. Another option being considered is sale to foreign countries that have less stringent regulations regarding use of contaminated metal. However, due to other priorities, decontamination efforts are not expected to begin for at least five years. According to Mike Jugan of MMES, the cost of decontaminating the metal is expected to equal the money received through sales, which he estimated at \$0.40 per pound. As a result, he is very interested in finding a DOE application for this radioactive material.

Current Inventories

The current Oak Ridge Reservation inventory of scrap aluminum, which has historically been 10-15 per cent of the scrap metal total, is an estimated 50,000-75,000 tons. The overall rate of scrap metal generation is estimated to currently be 1,400 tons/year.

Future Inventories

Ebasco Services estimates that in the future the percentage of aluminum will decline from the historical 15 per cent of the scrap metal total to 3 per cent of the total. Note, however, that the overall rate of scrap metal generation is expected to increase sharply from 1,400 tons/year over the next two decades as major D&D program activities are undertaken.

Ebasco projects that future D&D of the Gaseous Diffusion Plants (GDP) will result in scrap metal having the following makeup: 80-85 per cent ferrous metal/mild steel, 3 per cent aluminum, nil stainless steel, and roughly equal proportions of copper and nickel as the remainder. In addition to these metals, significant amounts of exotic metals such as tantalum, Inconel, and titanium may be encountered from time to time.

Ebasco estimates the total scrap metal tonnage that will be generated for the 3-Site GDP complex (Oak Ridge, Portsmouth, and Paducah) will be over 730,000 tons. Assuming that 3 per cent of that total is aluminum, 21,900 tons should be scrap aluminum. Ebasco estimates that over 300,000 tons of potentially contaminated metals (excluding major structural steel) could be generated from D&D of the GDP facilities at the K-25 Site. If 3 per cent of that total is aluminum, K-25 D&D activities should generate 9,000 tons of scrap aluminum, 41 per cent of the aluminum generated from the D&D activities at the 3-Site GDP complex. Lesser but significant quantities of contaminated scrap metals are expected to be generated from D&D programs at the Y-12 Plant and Oak Ridge National Laboratory.

Recycling Versus Disposal Costs

It is reported in the document, *Strategic Plan: Metals Recycle Technology for the Oak Ridge Complex* (H.W. Hayden, Jr., R.K. Kibbe, and B.E. Prince; Martin Marietta Energy Systems, Feb. 28, 1994), that radioactive material disposal costs run in the range of \$50 to \$100/ft³. Assuming disposal in a B-25-type container (with 6,000-lb. load limit), scrap metal disposal costs will be on the order of \$2,000 to \$4,000/ton.

Super compaction could significantly reduce the disposal volume and hence directly reduce the disposal cost, which is based on total volume. Commercial super compaction, however, costs nearly \$2,000/ton (\$1.15/lb.). Total weight is not particularly important as long as a suitable shipping/disposal container can be found that minimizes external container volume for a given scrap metal mass and special rigging is not required. The only scrap metal management requirement necessary to support off-site shipment and disposal is segregation of enriched uranium-contaminated metal from depleted metal to facilitate better accountability of special nuclear materials.

In comparison to disposal, the cost of an existing commercial service to fabricate shielding blocks from DOE scrap metal will be around \$2,000 to \$3,000/ton (\$1.00 to \$1.50/lb.).

Decontamination services cost in the range of \$700 to \$4,000/ton depending on the type and nature of the contamination and type of decontamination process. Grit blasting, liquid

abrasive washing, and high-pressure water spraying are examples of the more common physical processes. Chemical processes involve the use of acid/alkali solutions and various proprietary chemical agents in a washing or dissolution configuration. Melt-refining and electro-refining processes are required to purify volumetrically contaminated metals.

Another cost that must be considered is the cost required to verify that suspect scrap metal is sufficiently clean for unrestricted release. For example, it takes a health physics technician 30 minutes to survey a 4'x8' metal plate with a typical field survey instrument. Assuming two independent surveys (as required by local procedure), the verification cost will run nearly \$100 to \$200/ton for plate steel and over \$400/ton for plate aluminum (low metal mass per unit volume compared to steel). Considerably more technician time would be required to survey high specific surface area scrap (items with unusually high surface area per unit mass compared to plate or massive metal shapes), which are common in Oak Ridge scrap yards. Miscellaneous scrap metal monitoring could cost well over \$1,000/ton.

Decontaminated aluminum brings around \$600/ton on the secondary metal market. Unless the avoided costs associated with disposal (\$2,000 to \$4,000/ton) or contaminated metal fabrication (\$2,000 to \$3,000/ton) are taken into account, the economics of unrestricted ferrous metal recycle from scrap does not appear to be a good argument based on the value of scrap steel relative to decontamination and verification costs.

Organic Reduction in Acid

This technology is very old and was developed in Europe by the Germans. In this process, the nitrate-containing solution must be acidic before it can be utilized, and therefore vast amounts of acid would likely have to be added to the Hanford waste, depending upon waste-buffering capacity. In this process, acidic nitrate-based solutions are heated, and an organic compound such as sucrose, formaldehyde, or formic acid is slowly added to produce NO_x and carbon dioxide as well as a great deal of heat.

The process is difficult to control and is sometimes explosive. In addition, any acid chosen to lower the pH of the Hanford solution will create problems. Corrosion problems will follow the use of hydrochloric acid. Sulfuric acid will produce large amounts of the high-volume hydrated calcium sulfate (gypsum). Nitric acid may be the only remaining choice, even though it creates more nitrate, which must be removed later. Because nitric acid, like hydrochloric acid, provides only one proton, vast amounts of acid (and consequently nitrate) would be necessary if these acids were used.

THERMAL CONVERSION

Although the reported values for the initial temperature of thermal decomposition of sodium nitrate vary widely, depending upon the reference source, decomposition starts at about 588°C and is 70 per cent complete at about 940°C. This conversion to NO_x and sodium oxide can occur only after all water has been evaporated—a very energy-intensive process step.

According to Frank Wooley of Corning Glass, adding a liquid feed to a cold-top or Joule melter will add 30-40 per cent to the energy cost. It will also decrease the life of the furnace electrodes and cause corrosion. While a typical furnace can last from less than one to five years, he predicts that without making changes to the design, the life will be decreased by one third or even much greater. He suggests that a combustion-fired melter might offer better efficiencies. However, a liquid at less than 1,000°C can cause thermal shock to the refractories resulting in shorter life.

A problem for thermal technologies is that the scrubbing of NO_x is still partly science and some art. The lower oxides of nitrogen, which have a low aqueous solubility, are often not removed and need to be reoxidized and rescrubbed in many stages, only to produce another nitrate/nitrite-contaminated waste stream, possibly containing radioelements. Additionally, radioelements that become volatile in the temperature range of 588 to 1,200°C must be scrubbed out, thereby producing yet another separate waste stream.

In addition to problems with NO_x and radioelement scrubbing, organics present in the nitrate-based waste may initiate an explosion depending upon concentration, and other catalyzing metals or species that may be present in the waste.

Nitrate Destruction

The basic thermal destruction or decomposition of nitrate salts is easily accomplished and was a common practice in past years. Sodium nitrate will decompose at a relatively low temperature (about 650°C). However, it releases the nitrogen as mixed oxides, NO_x , which can no longer be simply released to the atmosphere.

Thermal processes that destroy nitrates with the creation of less than 500 ppm NO_x as a by-product have been demonstrated. Note that the cost per ton of NO_x removal increases dramatically with decreasing NO_x concentration. According to Phillip Cook of Air Products, the cost of reducing 500 ppm NO_x to 50 ppm can cost as little as \$1,000-2,000 per ton NO_x . However, decreasing the concentration from 100 to 20 ppm can cost \$8,000 per ton NO_x .

Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies reports on studies that were performed on a molten salt destructor, a high-temperature fluid-wall reactor (HTFWR), a glass furnace, a plasma arc furnace, laser excitation, and microwave heating. Preliminary tests showed that the HTFWR and the molten salt destructor produced excellent destruction of nitrates without producing significant amounts of NO_x by-product.

Different types of decomposition are reported throughout the literature.

Direct Thermal Decomposition

This process involves the direct heating of nitrate waste to its decomposition temperature. Although this may be the simplest and most direct method, it has some drawbacks. The possible generation of NO_x in the off-gas is a major problem, but its generation might be eliminated or reduced to a low amount by proper application of temperature, time, pressure, or additives. The composition of the waste could hinder the thermal destruction as well as generate HCl , SO_2 , and other gaseous decomposition products. The presence of these and NO_x in the off-gas would require a gas scrubber, and probably a catalytic reactor with NH_3 injection to reduce NO_x to discharge limits. Additional problems would also be encountered in equipment downtime, resulting from the corrosive nature of the waste. A proper choice of material for fabricating process equipment would be important.

Thermal Reaction

There are several mechanical approaches to this method of nitrate waste treatment. The basic mechanism involves the controlled reaction of nitrates with an additive, usually carbon, in a heated matrix. Nitrates are reduced to N_2 and CO_2 , which can be safely discharged. The residue would then be a carbonate, a more desirable waste form.

A number of variations of this process have been tried with little or no detectable NO_x generation. Configurations that would lend themselves to continuous or batch processes have been devised. Most of the problems reported were mechanical in nature and could probably be solved. Perhaps the most significant drawback is the generation of a voluminous end product.

High-temperature Processes

There are several types of high-temperature processes that offer the possibility of disposal mechanisms.

Calcination—Fluidized Bed

Calcining is a well established process at INEL for solidifying low-sodium concentration waste streams, but it is not applicable to the alkaline wastes stored at most other DOE facilities.

Aqueous radioactive wastes at INEL are stabilized and solidified in a fluidized-bed calcining facility called the New Waste Calcining Facility (NWCF). The 1.5-meter diameter calciner, which is heated to $500^\circ C$ by in-bed combustion, will process about 200 gallons per hour of waste, producing a dry granular solid for storage. The NWCF treats a variety of waste waters, including wastes high in aluminum, zirconium, fluoride, and ammonia as well as nitrate.

The concentration of sodium nitrate in the feed is strictly controlled to prevent caking of the calcine. Sodium nitrate melts at $308^\circ C$, and mixtures of sodium nitrate with potassium, calcium, or magnesium nitrate melt at even lower temperatures. Sodium nitrate decomposes to produce Na_2O and NO_2 in the range of 600 to $900^\circ C$, which is above the temperature limit for the NWCF. Small amounts of sodium-bearing wastes are calcined by mixing them with other waste solutions, but inventories of sodium wastes are accumulating because of the limited amount of sodium allowed in the NWCF. According to B.H. O'Brien of INEL (personal communication to P.A. Taylor, ORNL, March 24, 1993), the cost for calcining waste in the NWCF is about \$37/L (\$130/kg nitrate).

Pilot-scale tests have demonstrated that the ratio of sodium wastes entering the NWCF can be increased by adding sucrose to the waste solution. The sucrose reacts with the nitrate to produce NO_x , as described in the chemical reduction process section of this report. Potential problems identified in the pilot-scale tests include possible plugging of off-gas filters by unburned sucrose, increasing the amount of fines produced, and caking of the solids during storage.

Calcination—Plasma Furnace

At high temperatures ($>2,000^{\circ}$), nitrates can be converted directly to nitrogen gas. Pilot-scale tests using a plasma torch have demonstrated that a mixture of sodium nitrate and potassium nitrate can be converted to solid carbonates and nitrogen gas. The equipment consisted of a plasma torch, which generates extremely high temperatures by passing nitrogen or argon gas through a magnetically rotated electric arc producing an incandescent stream of ionized gas, and a graphite-lined, coke-filled furnace that served as a reaction chamber. The coke reacted with the sodium and potassium oxides produced by the torch to yield carbonates.

An aqueous waste, consisting of magnesium, aluminum, and calcium nitrates and nitric acid, which simulated a raffinate waste produced at the Feed Materials Production Center at Fernald, was also calcined using a Westinghouse Marc 3 plasma torch. The torch was operated at a power level of 98 to 173 kW with air as the carrier gas, which yielded a reactor temperature of about $1,200^{\circ}\text{C}$. The raffinate simulant was fed to the torch at a flow rate of 0.25 L/min. The reaction product was primarily metal oxides containing <1 per cent nitrates. With air as the carrier gas, the torch generated about 1,800 ppm NO in the off-gas prior to feed addition, which increased to about 2,100 ppm NO after feed addition. Most of the nitrates in the feed were converted to nitrogen gas.

Plasma torches generate extremely high temperatures by passing compressed gases through a rotating high current electric arc. The resultant incandescent stream of ionized gas, or plasma, flows out at temperatures as high as $7,000^{\circ}\text{K}$. Virtually any type of gas can be heated, whether oxidizing, reducing, or inert. Note that there are no plans to do further testing with this method for nitrate salts because the present equipment layout is not suitable for the collection of residues required for operation and a material balance would be difficult to obtain.

Hydrothermal Process

The hydrothermal process is a variation of the chemical reduction process, with the chemical reduction occurring at higher temperatures and pressures. The same range of reducing agents could be used, but more refractory compounds such as ferrocyanides, which may be present in the waste, will also react with the nitrate under these conditions.

This technology has been tested in laboratory-scale experiments using a surrogate for the Hanford tank waste and other more dilute nitrate solutions. These tests showed that formic acid can be used to destroy essentially all of the nitrate in a 3 wt.% nitrate solution within two hours under acidic (pH 4) or basic (pH 13) conditions. For pH 13, this method is possible only under very high pressure (350°C , 19 Mpa). In the acidic solution, essentially all of the nitrate was converted to nitrogen gas, but in the basic solution only about 50 per cent was converted to nitrogen gas, and the remainder was unaccounted for. Other reductants such as ammonia, urea, methane, and hydrogen, were tested under similar conditions, but they were found to be less effective, particularly at high pH.

Laboratory-scale tests have demonstrated that various organics and ammonia will react with nitrate under supercritical or near supercritical conditions (450 to 525°C , 30 Mpa). A mixture of nitrogen gas and nitrous oxide is produced from the nitrate. Potassium ferrocyanide, which is present in the Hanford waste, will react with nitrate at 500°C and 30 Mpa. Most salts are only slightly soluble in supercritical water. For example, sodium nitrate has a solubility of 293 ppm at 525°C and 24.8 MPa. Low solubility may make it difficult to get high sodium-nitrate-concentration solutions into the reactor, but also opens

the possibility for removing the reaction products (i.e., sodium hydroxide) and other radionuclides and heavy metals as a solid waste.

This process has the potential for destroying nitrates in both acidic and alkaline wastes without any required pretreatment. Under some conditions, the nitrate is converted almost completely to nitrogen gas. A major advantage of this method is that organics present in the waste are destroyed along with the nitrate. The organics are converted to carbon dioxide and minerals. It may be possible to separate most of the salts and some radionuclides and heavy metals as a solid waste. If the majority of the salts are removed from the supercritical water in the reactor, the dilute solution remaining could be greatly reduced in volume by evaporation before solidification, which is required for final disposal.

Because nitrates and other salts have limited solubility in supercritical water, plugging of the lines to and from the reactor is a concern. Because the high temperatures and pressures used in the process will increase corrosion rates, exotic materials will probably be required for the reactor. Off-gas treatment may be required for NO_x .

Molten Salt Destructor

Many nitrate salts, such as sodium nitrate, when in the molten state will react with powdered carbon to form a carbonate salt, i.e., sodium carbonate. The generation of NO_x is minimal, with nearly all of the nitrogen being released as nitrogen gas, N_2 . Sodium carbonate is inert and amenable to immobilization techniques, if necessary. An approximate 35 per cent weight loss is a secondary advantage. The low-melting temperature of about 400°C for the waste mixture had advantages as to equipment and materials of construction. As experience was gained in testing and preliminary operating parameters were established, the NO_x levels were optimized to less than 100 ppm in the final run.

Steam Reforming

Synthetica Technologies' commercial steam reforming process is being investigated for the destruction of organic materials and decomposition of nitrates in mixed wastes. This project will address mercury processing, nitrate decomposition (aqueous processing), and organic destruction. This project will use a commercial one ton/day steam reforming system, located in California.

The system uses a high temperature reactor ($1,200^\circ\text{C}$) called a Thermal Detoxifier, which is equipped with several feed systems designed to gasify different waste forms (e.g., drummed wastes, liquid wastes, slurried wastes, medical wastes, low-level radioactive wastes, and contaminated soil). Wastes are gasified in the appropriate feed system by exposure to superheated steam, and then the gasified organic materials are fed to the Detoxifier, where they are destroyed by heat. When the organic materials in the waste contain substantial amounts of heteroatoms, acid removal is performed to prevent corrosion.

Vitrification

Vitrification is a physical encapsulation technique that has been accepted for high-level waste. It results in a net volume reduction, even starting with a bed of solids and no liquids. This results in significant economic savings for ultimate disposal to compensate for the higher capital and production costs to generate this waste form compared with

cementitious waste forms. Ostensibly, there is no interaction with the waste, but it is questionable whether vitrified waste will pass the TCLP test. The waste form is non-porous and less leachable than cementitious waste forms, but the RCRA metal may be just as extractable after treatment as before, if truly allowed to come into equilibrium as intended in the TCLP test.

Because the process operates at elevated temperatures, it drives off water and destroys organics, although in some cases large amounts of liquid, including water, may slow the vitrification rate. Volatiles and semivolatiles that cannot be destroyed include mercury, tritium, cesium, and technetium. Wastes containing these contaminants, which are commonly found in low-level radioactive waste, may not be amenable to vitrification.

Vitrification will be used by DOE's Savannah River and West Valley Sites to treat high-level radioactive waste. Savannah River is expected to begin running radioactive material in a couple of years. The final waste form that results from vitrification, borosilicate-based glass, is predicted to be stable for thousands of years. The use of vitrification has not yet been demonstrated as cost-effective for mixed low-level radioactive waste.

Efforts are underway to modify the proven high-level technology with adaptations from commercial melting processes for the treatment of low-level mixed wastes. These efforts include realistic simulation and pilot-scale testing, and examining factors such as waste form quality, potential for air emissions, and economics. Initial efforts include developing glass/ceramic waste forms and demonstrating processes that use commercially available melters, which should prove to be more economically viable. These results will allow systems analysis and cost/benefit comparisons to evaluate options regarding up-front separation of problem components or off-gas treatment. Off-gas temperature in the cold-top furnace has been monitored and found generally to be below the temperature range where significant volatilization of toxic metals occurs.

Process Description

The vitrification process uses high temperatures (typically between 1,100 and 3,000°C) to chemically incorporate wastes into a glassy matrix. Unfortunately, according to industry sources, this temperature range is the worst for producing NO_x emissions.

Vitrification involves cooling the hot amorphous liquid fast enough to prevent crystallization from occurring in order to form an amorphous supercooled liquid (i.e., glass). Any material, even metal, can be vitrified depending on how it is processed. As a result, the vitrified material has properties that are much different from a crystalline version of the same material. From a practical point of view, the problem is that many materials are difficult, if not impossible, to cool fast enough.

At elevated temperatures, glass becomes electrically conductive, and the current passing between the electrodes in a vitrifier causes the conductive glass to heat, thereby maintaining the glass in the molten state. This process is known as joule-heating. Most inorganics oxidize and dissolve in the molten glass because the great majority of oxides are soluble in silicate glasses; organics rapidly oxidize at the high temperatures and form simple gases (mostly carbon dioxide and water vapor) that are collected and treated in the off-gas system.

Materials Produced

A glass by definition is a completely amorphous solid, whereas a ceramic is largely crystalline with fused grain surfaces. In between these two extremes are a wide variety of glassy ceramics in which crystalline phases are dispersed throughout a glassy continuous phase. Such materials may include slags, which incorporate various metal oxides. These waste forms are also under evaluation and show promise for long-term stability and leach resistance.

Glass or glassy ceramic (slag) waste forms produced by vitrification are unique in that they can easily accommodate a wide range of metal oxides into their structure and still produce a stable and durable material. The amorphous structure of the glass phase allows this incorporation of many constituents as a part of the glass structure itself rather than simply being encapsulated by the glass.

Glasses behave differently due to their environment and chemistry. Desirable glass behaviors include: 1) melting at a relatively low temperature, 1,100°C (2,000°F), 2) having a specific electrical conductivity, and 3) good leaching resistance. The inorganic chemical elements present in a glass greatly affect its viscosity/temperature relationship, which is often referred to as the viscosity behavior. Fluxes are added to lower the viscosity at a given temperature. Achieving a behavior that is practical to work with requires an intricate knowledge of the effects of various elements on the glass.

In order to melt glass in a joule-heated (electric) melter, it must have a specific electrical conductivity. The conductivity is affected by the chemical elements present in the glass. Adding fluxes increases the conductivity.

The leaching resistance of the glass to acidic soil is the most important behavior of all. Leaching is the process of the chemical elements of the glass being pulled out of the glass surface and into the ground water or soil. Depending on the recipe of the glass, it can be designed to leach at a minimal level. Adding the fluxes mentioned above can lower the leaching resistance of the glass. To counter this, other things can be added to increase the leaching resistance. The problem is that adding a chemical to achieve one effect may cause some side effects.

Melting Equipment

To date, work has focused almost entirely on a low-temperature, joule-heated melter system. However, a variation of vitrification technology can instead use a plasma or microwave system, which operates between 1,800 to 2,600°C. In such a system, a more viscous glass or slag can be produced with fewer limitations on metals content or organics in the waste streams chosen. Initial evaluation tests are underway using the Plasma Centrifugal Furnace (PCF) technology from Retech, Inc. MSE, Inc. is coordinating these tests.

High-temperature Fluid-wall Reactor. One of the reactors employs a high-temperature fluid-wall (HTFW) process where the waste salt is elevated to a high temperature, resulting in a very fast thermal reduction of both nitrated and any generated NO_x. Pilot testing showed that the process met the RFP criteria for a successful demonstration. A variation is the fluidizing of the nitrate waste with an inert support media and then reacting it with a reducing gas. The main advantage to this approach would be the volume reduction in the residue.

Joule-heated Glass Furnace. A thermal system tested that operated in a similar temperature range as the molten salt reactor is the joule-heated glass furnace. The glass furnace is an elongated chamber containing a pool of molten glass. The glass pool, contained in a bed fabricated of fused-cast refractory, is heated by iron electrodes protruding horizontally into the glass. Gases exit the furnace through an exhaust port at the end of the chamber opposite the feed port and enter a wet off-gas system, which consists of primary and secondary recirculating wet scrubbing equipment, followed by a high efficiency filter. Tests indicate that the joule-heated glass furnace can effectively process RFP nitrate waste while maintaining emission levels under 500 ppm.

Limitations

It is questionable whether vitrified waste will pass the TCLP test. Although the waste form is non-porous and less leachable than cementitious waste forms, the RCRA metal may be just as extractable after treatment as before, if truly allowed to come into equilibrium as intended in the TCLP test. The high process temperature, which drives off water and destroys organics does not destroy other volatiles and semivolatiles. Those materials that cannot be destroyed include mercury, tritium, cesium, and technetium. Of the priority pollutant metals, mercury is known to escape from the glass during vitrification due to its high vapor pressure.

The process is not amenable to waste solutions with significant concentrations of sulfates (i.e., <2% on a dry solids basis). Sulfate solubility in glass is limited to 0.5 wt.%. The amount of glass produced is expected to be determined by the fluoride solubility limit in the glass. Fluoride, a major constituent in the raffinate sludges, has a maximum glass solubility of about 5 wt.%.

Minimum Additive Waste Stabilization Project

Minimum Additive Waste Stabilization (MAWS) is a new approach to vitrification. The process provides an environmentally sound alternative for the vast amount of low-level radioactive/mixed waste that exists within the DOE complex. MAWS utilizes multiple waste streams as substitutes for additives (i.e., glass formers and fluxes) necessary for vitrification to produce a stable, high-quality waste form. MAWS results in the minimum waste volume for disposal.

If too much glass former is present, then the melt viscosity or temperature will be too high for processing. If there is too much flux, then the durability may suffer. Therefore, there are optimum combinations of these constituents depending on the criteria required. The challenge is to combine these resources in such a way that minimizes the use of non-waste additives yet yields a processable and durable final waste form for disposal. The benefit to this approach is that the volume of the final waste form is minimized (waste loading maximized) since little or no additives are used and vitrification itself results in volume reduction through evaporation of water, combustion of organics, and compaction of the solids into a non-porous glass.

The first pilot scale demonstration and evaluation of the MAWS technical system will be implemented at Fernald, OH. GTS Duratek has operated its DuraMelter 300 (300 kg/day) at the Fernald Environmental Management Project (FEMP). Using feed material

chemically similar the FEMP wastes, the company successfully made glass, DuraGems, in the first phase of the MAWS demonstration project. Although the melter's rated output was 300 kilograms (about 600 pounds) per day, it ran smoothly up to twice that rate. Westinghouse Savannah River Co. awarded GTS Duratek a \$13.9 million contract to process wastes on a pay-for-performance basis (i.e., payment per gallon of waste processed, which is expected to save 20-30% compared to competing technologies). This entails building a commercial-scale (5 ton/day nominal glass output) DuraMelter. This will be the largest commercial-sized unit in the world actually processing low-level mixed wastes on an environmental remediation project.

GTS Duratek and its partner, Catholic University of America's Vitreous State Laboratory, was awarded a contract by Argonne National Laboratory to study waste streams at DOE sites across the country. The company will characterize the various wastes and develop a database that will enable DOE to quickly determine whether the MAWS technology can be applied for long-term stabilization of those wastes.

Fernald Integrated System. Application of the MAWS concept may take many forms of integrated systems that will be dependent on the particular waste streams being combined. The particular integrated system chosen for Fernald consists of vitrification, soil washing, and ion exchange/water treatment.

The MAWS vitrification off-gas system at Fernald will have an advanced two-stage caustic scrubbing system designed to produce no secondary waste streams. The off-gases will then be treated by high-efficiency particulate air (HEPA) filtration to meet regulatory requirements for release. Produced sludges will be recycled to the melter. Monitoring equipment will also be provided.

Assumptions. The glass volume factor decrease is roughly 0.75. This is supposedly a conservative estimate based on moisture of sludge, organics in soil, and waste loading percentage. The actual volume decrease could be closer to 0.50. The vitrification option is for four equally sized melter systems, each at about 80 tons/day capacity and projected to complete operations in 10 years. The on-line operational rate is projected to be 75 per cent, or normally three operational and one system down for maintenance. Operations include slurry/retrieval, mixing, melting, handling of glass gems, and waste water treatment. Glass (as gems) does not require placement into a container as it will pass leach test requirements in that waste form.

SOLIDIFICATION/STABILIZATION METHODS

Numerous tests have been conducted on incorporation/encapsulation of nitrates within different matrices, perhaps the most common being concrete. Although this method is currently being used to immobilize radioactive nitrate waste (usually at a small waste loading), the water leach resistance for the contained nitrate is minimal. It also greatly increases the weight of waste material. Concrete waste forms, to have acceptable leach resistance, would require an add-on coating of some type. Instead of coatings, however, this material is placed in concrete vaults to prevent ion migration. A detailed description of other stabilization methods and materials can be found in Chapter 5, *Treatment Issues*.

GROUTING

Solidification/stabilization (i.e., grouting) is one of the most widely used techniques for the treatment and ultimate disposal of hazardous wastes and low-level radioactive wastes. Cementitious materials are the predominant materials of choice because of their low associated processing costs, compatibility with a wide variety of disposal scenarios, and ability to meet stringent processing and performance requirements.

Grout, as planned for near-surface disposal, was included in the HDW-EIS Record of Decision. However, stakeholder concerns about its performance for immobilizing LLW over a long period of time (leachability) and life-cycle cost estimates for other LLW forms being no greater than grout raised questions about continuing with grout. Other factors such as high radionuclide content, lack of retrievability, and large number of vaults to be constructed added to the concern.

Process Description

The concept for the grouting process is to mix a waste slurry with cementitious materials to form a grout that can be pumped to a vault. The grout solidifies in the disposal site into a massive monolith. The disposal site has engineered features to collect leachate, prevent ionic diffusion, and to protect the grout from water infiltration.

Cementitious Materials

Cementitious materials include cement, granulated blast furnace slag, fly ash, lime, and silica fume. Various clays and additives are used to help immobilize contaminants or otherwise enhance the waste form properties. Soluble constituents in the waste chemically interact with the cementitious materials to form low-solubility products at the low pH and the Eh prevailing in the waste form. These interactions usually affect the cementitious hardening and properties to some degree. Testing with a specific waste or waste stream is required to tailor the formulation to the desired properties. Sufficient attention must be given to characterizing the waste, developing the formulation to treat the waste, and to implementing this formulation in the field to assure correct mixing of the formulation.

Volume Increase

Adding these dry ingredients inevitably increases the volume of the waste treated, which can add significantly to the lifetime disposal costs. The volume decrease claimed, such as thermoplastic encapsulation, comes from evaporation of the water and encapsulation of the solids. The same evaporation pretreatment could be used with cementitious S/S to obtain a net volume decrease. The cementitious waste forms are porous, making them more leachable than polymeric or glass waste forms. The key has been controlling this leachability (by pH, Eh, and/or absorbents) within satisfactory limits for a simpler and cheaper treatment.

In the case of cement-based grout, large volume increases result when an aqueous waste is placed in such a matrix. The cementation volume factor increase is roughly 3.75 at the Fernald site. This is due to the difficulty of immobilizing technetium (Tc 99), which is present in the waste, and to achieve a 500 psi grout waste form. Fly ash is used as an additive. Cementation will require placement in 4' x 4' x 8' steel B25 containers to serve both as a mole and for ease of handling the finished blocks.

Dangerous Waste Designation and Limitations

Cementitious materials are ideal for macroencapsulating relatively inert materials such as rubble or scrap metal. However, encapsulated ion-exchange resins can lead to breakdown of the solid matrix because of the volume changes that result from wetting and drying of the resin. Proper formulation and pretreatment of the resin have succeeded in overcoming this problem for encapsulated resins.

The salt grout process, which is based on formulations being developed for disposal of double-shell tank LLW, will not modify or remove listed waste constituents from the product stream and thus may be subject to listed waste regulations. Grout is an extremely hazardous waste by the book designation procedure for toxic dangerous waste. The major contribution to this designation is nitrite. Disposal of a listed waste increases disposal costs and complicates pilot plant investigations.

When grouting is used to treat nitrate-laden aqueous waste, the nitrates generally increase the volume and/or reduce the integrity of all the final waste forms that have been proposed for ultimate disposal. As a result, nitrate destruction prior to solidification is expected to be beneficial.

Because nitrate is such a mobile anion, it is difficult to immobilize. No cement-based formulation is known that can prevent the diffusion of nitrate or nitrite out into the environment when water is present. Materials such as polyethylene and bitumen are subject to osmotic pressure swelling over time and can burn on their own, once ignited with difficulty, because nitrate carries its own oxygen.

Because of the ease with which nitrate is leached from grout, it is placed inside concrete vaults to slow release. The pore water inside the vault walls will eventually equilibrate with the nitrate ion concentration in the grout pore water and then release to the environment begins. In this case, the vault is another barrier that will eventually release nitrate as well, but at a reduced rate. The vault is also subject to degradation by the elements and the forces of nature with time.

Savannah River

Portland cement grouts were chosen for the Savannah River project because of their flexibility in processing, durability, and ability to adjust properties for the desired waste characteristic. The ability to adjust properties was important since one of the options is to pump the cemented waste to the on-site burial grounds. After casting and testing formed specimens from several trial formulations, the formulation shown in Table 29 was selected as the current reference saltstone. Three 30-ton monoliths using this formulation were cast and installed in lysimeters for field testing.

TABLE 29
SAVANNAH RIVER SALTSTONE REFERENCE FORMULATION

INGREDIENT	WEIGHT PER CENT
Cement	
Fly ash (Class C)	48
Portland cement (Class H)	12
Solution	
Water	27
Salt	13

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

CHAPTER 5. TREATMENT ISSUES

There are several treatment issues relevant to this report that will be discussed in this chapter. These issues are: feed pretreatments (i.e., volume reduction, radionuclide removal, and organic destruction), off-gas treatments, final waste forms, and materials of construction.

FEED PRETREATMENTS

Many different feed pretreatments are being discussed and evaluated by DOE for the aqueous nitrate tank waste. Because the selection of a pretreatment train must be made on a case-by-case basis for a particular waste stream, KEI was forced to make some simplifying assumptions in its analysis. The volume of waste to be treated in the analysis scenario is based on the tank volumes presented in Table 9, which can be found in Chapter 3. These volumes were not adjusted to account for volume changes that result from pretreatments.

VOLUME REDUCTION

In the process of treating the HLW, around 80 per cent of the HLW volume will be converted to LLW, which will be treated separately by a process yet to be determined. Note that, because of the large uncertainty surrounding the development of a federal repository for HLW, the concept of minimizing the volume of glass for storage was viewed by stakeholders as far less important than getting on with the cleanup. As a result, it was felt that a Hanford HLW Immobilization Facility could be built and operations could be started sooner by switching the development emphasis from the higher-risk extensive separations towards the lower-risk development of higher capacity melters. If new cost-effective separations technology for pretreatment were to come along later, that technology could be incorporated to enhance the process.

RADIONUCLIDE REMOVAL

It has been reported that the performance of the on-site disposal waste form can be improved by removing TRU, ^{90}Sr , and ^{99}Tc from alkaline waste solutions. The concentrations of TRU and ^{90}Sr are high in some alkaline wastes because these radionuclides exist as soluble complexes with organic chelating agents. Technetium is present as the soluble TcO_4^- anion. Methods for removing these radionuclides from alkaline waste solutions are not well developed. However, initial scouting tests are underway. Further testing is warranted because of the possibility that simple carrier precipitation or scavenging methods (e.g., hydroxide adjustment for precipitation of TRU and ^{90}Sr , sulfide precipitation of ^{99}Tc , and strontium isotopic swamping) could potentially be performed in-tank.

In those cases where solvent extraction technology is either not available or, for some reason, not desirable, fixed-bed ion exchange processes are usually preferred over precipitation or extraction chromatographic processes. Fixed-bed load-wash-elute ion exchange processes were successfully used on a plant-scale at the Hanford Site to separate megacurie amounts of ^{137}Cs . Precipitation processes also have been used at Hanford for separation of plutonium, ^{137}Cs , ^{90}Sr , and fission product rare earths.

Precipitation processes are batch rather than continuous processes. Simple batch precipitation processes typically are incapable of removing >99 per cent of a particular radionuclide or group of radionuclides and also do not provide acceptable decontamination of separated radionuclides from contaminants. Extraction chromatographic processes are useful for small volume highly specialized separations, e.g., trivalent actinides from trivalent rare earths. Because of capacity and selectivity limitations, they are not particularly useful for handling large volumes of feeds.

Acidic Wastes

TRU Elements and ⁹⁹Techneium

For reasons already stated, liquid-liquid extraction processes are preferred over precipitation (e.g., oxalates or fluoride) processes or extraction chromatographic processes for separation of TRU elements from acidified wastes. Bifunctional extractants (e.g., carbamoylmethylene phosphine oxides (CMPO/ or diamides)) are much preferred over monofunctional reagents such as dibutylbutylphosphonate because they efficiently extract Am³⁺ as well as +4 and +6 actinides from strongly acidic (i.e., >0.5M HNO₃) feeds. For several reasons (e.g., commercial availability, ability to co-extract ⁹⁹Tc, decontamination potential, etc.), one particular CMPO, namely octylphenyl-N, N-diisobutylcarbamoylmethylphosphine oxide, is the currently preferred TRU element extractant.

⁹⁰Strontium

Processes that effectively and selectively remove ⁹⁰Sr from strongly acidic solutions are difficult to devise. The currently best available technology appears to be the SREX process, a solvent extraction process using a commercially available crown ether diluted with n-octanol or TBP and NPH as the extractant. The SREX process is highly selective for Sr²⁺ over a wide range of feed acidities; only Ba²⁺ co-extracts to any extent. Dilute HNO₃ solutions readily strip Sr²⁺ from the solvent.

Two other processes are potentially available for separating ⁹⁰Sr from acidic media. One of these is the dicarbolide solvent extraction process long studied by both Russian and Czechoslovakian scientists. According to these investigations, dicarbolides effectively and selectively extract both Cs⁺ and Sr²⁺ from acidic media provided a polyglycol is added to the feed. A major, perhaps insurmountable, disadvantage of the dicarbolide extraction process is that the required diluents are nitrobenzene or chlorinated benzenes. Such toxic diluents are no longer acceptable for use in U.S. nuclear separation plants.

Crystalline polyantimonic acid also effectively and selectively sorbs ⁹⁰Sr from nuclear acidic wastes. The principal disadvantage to this ion exchanger is that no single and inexpensive way of eluting sorbed ⁹⁰Sr is known. There are also concerns about the commercial availability of plant-scale quantities of crystalline polyantimonic acid.

¹³⁷Cesium

A need to remove ¹³⁷Cs from acidic waste solutions has not been established. If such removal is required from some acidic solutions, the simplest procedure is to adjust the acid waste to pH 9-10, after prior removal of TRU elements and ⁹⁰Sr, and use well-known ion exchange materials and procedures for removal of ¹³⁷Cs.

Subject to the limitations discussed earlier, a batch precipitation of cesium phosphotungstate (PTA) could be used to remove about 95 per cent of the ^{137}Cs directly from the acid waste. Alternatively, it may be feasible to remove ^{137}Cs from the acid waste by means of the cesium-strontium extraction process. The latter is a solvent extraction process currently just under development at the Argonne National Laboratory; the extractant is a commercially available crown ether. Crystalline sodium titanate has also been reported to sorb ^{137}Cs from acidic media.

Alkaline Wastes

^{99}Tc Technetium

The classic and preferred way of removing ^{99}Tc from alkaline waste solutions is to selectively sorb it, as TcO_4 , on a strong-base organic ion exchanger. Sorbed ^{99}Tc can be eluted with 6M HNO_3 solution.

Various organic compounds (e.g., cyclohexanone, pyridine, tetra propylammonium hydroxide) are known to extract ^{99}Tc from alkaline wastes. Of these reagents, cyclohexanone appears most promising and has been studied on a bench-scale with actual Hanford wastes. Further work, including pilot-plant-scale tests with the cyclohexanone extraction process, are required to determine the extent of emulsion problems in solvent extraction of the alkaline waste solution.

^{137}Cs Cesium

Organic cation exchange resins were used very successfully at Hanford on a plant-scale for many years to remove ^{137}Cs from alkaline wastes. Such technology using newer resins (e.g., CS-100 or a resorcinol-based exchanger developed at the Savannah River Site) is still the preferred technology for removing ^{137}Cs from alkaline tank wastes.

Alternative methods for removing ^{137}Cs from alkaline solutions all appear to have disadvantages compared to well-established ion exchange technology. Thus, various precipitation agents (e.g., tetraphenyl boron, nickel ferrocyanide, etc.) must all be applied on a batch basis and, in a single precipitation step, may not give required yields. Furthermore, downstream treatment of the Cs-laden precipitates involves potential safety hazards. Candidate solvent extraction processes employing such extraction as BAMBP, dipicrylamine, polybromides, and crown ethers have not either been fully developed or require use of toxic diluents such as nitrobenzene.

DESTRUCTION OF ORGANIC COMPLEXANTS

It is sometimes important to remove organics from a waste feed because of interference with process effectiveness. Leading candidates for organic destruction include heat and digest, supercritical water oxidation (SCWO), and incineration. In-tank digestion will degrade components that result in hydrogen generation (e.g., HEDTA). Incineration and SCWO will degrade organics to CO_2 and H_2O , and will also precipitate ^{90}Sr and TRU elements. Other candidates, including wet oxidation and steam reforming, may be competitive with SCWO but need further development.

OFF-GAS TREATMENT

This section discusses off-gas treatment and reuse issues for the NAC/NAG/NAX process and for vitrification.

NAC/NAG/NAX: AMMONIA

The off-gas from the NAC/NAG/NAX process consists of ammonia, hydrogen, water, and an inert purge gas such as nitrogen. Hydrogen produced in this process may be acceptably managed by discharging under non-explosive conditions, although almost any catalytic process for ammonia treatment under oxidizing conditions will convert it to water. Sulfur will be discharged as SO_3^- from the NAC/NAG/NAX reactor in the product slurry. If this slurry is exposed to oxidizing conditions, such as might be encountered in incorporation of NAC/NAG/NAX solids in glass, then SO_2 will ultimately report to the off-gas stream. SO_2 removal is discussed in the treatment of off-gas components from thermal decomposition.

The Statement of Work for this project indicated that KEI should assume the ammonia generated by the NAC/NAG/NAX process would be reused. However, discussions with industry sources have lead KEI to conclude that this is not economically feasible for the ammonia generated by the NAC/NAG/NAX process, primarily because of the water that is present in the reactor off-gas. Nevertheless, see the section entitled "Reclamation/Reuse" later in this chapter for a discussion of the reuse options for ammonia.

VITRIFICATION: NO_x

Because vitrification is conducted at high temperatures [$\geq 1,000^\circ\text{C}$ ($1,832^\circ\text{F}$)] and gas-producing materials may be included in the feed, an off-gas system is usually required. Classes of off-gas constituents that are commonly controlled during vitrification include the following:

TABLE 30
VITRIFICATION OFF-GAS CONSTITUENTS

- Entrained feed material
- Toxic metals (volatile and semi-volatile)
- Organics
- Sulfates and sulfur oxides (SO_x)
- Nitrogen compounds (NO_x)
- Carbon monoxide (CO)
- Hydrogen, halides, and halogens
- Mercury, selenium, arsenic, cadmium, and lead

Controlling NO_x emissions, one of the most common air pollutants, has become a top priority for all major urban areas. Unfortunately, it is one of the most difficult pollutants to remove. "Total NO_x " is the combined sum of NO and NO_2 . Like sulfur oxides, NO_x is mainly formed during combustion, although a few industries emit this gas from process operations such as rotary kilns and calcinators. NO_x is a primary component of urban smog. It is a powerful lung irritant and causes vegetation damage. It is easily distinguishable at the stack as a brown plume if the NO_2 ratio is high enough. It is toxic by inhalation, especially NO_2 .

While federal U.S. standards for NO_x are now 45 ppm, it is predicted that the future standard will be 10 ppm. According to *Perry's Chemical Engineers' Handbook*, as of 1983 the national primary and secondary ambient-air-quality standard for nitrogen oxides is 0.05 ppm ($100 \mu\text{g}/\text{m}^3$) based on an annual arithmetic mean. However, the emission level standard (40 CFR Part 60) varies by the type of facility. For *fossil-fuel-fired steam-generators*, the NO_x emission level is 0.70 lb/million BTU for coal-fired boilers, 0.3 lb/million BTU for oil-fired boilers, and 0.2 lb/million BUT for gas-fired boilers. For *electric utility steam generating units*, the NO_x emission level is 0.60 lb/million BTU for coal-fired (and coal-derived fuels) boilers. For oil-fired boilers, the NO_x emission level is 0.30 lb/million BTU. For gas-fired boilers, the level is 0.20 lb/million BTU. For *nitric acid plants*, the level is 3.0 lb/ton. Continuous monitoring is required for emissions greater than or equal to 40 tons/year NO_x (as NO_2).

Regulations controlling these emissions are most stringent in Southern California districts that fall within the jurisdiction of the South Coast Air Quality Management District (SCAQMD). The SCAQMD non-attainment rules demand that emissions be capped at pre-1980 levels. Maximum allowable emissions for individual companies are calculated on the basis of the total mass of material.

Sources

NO_x comes from manufacturing sources such as high-temperature combustion; metal cleaning, fertilizer, explosives, nitric acid; carbon-arc combustion; and the manufacture of H_2SO_4 .

One major source is from the oxidation of the fuel-bound nitrogen (fuel NO_x) and the other is by the fixation of nitrogen in the air at the high temperatures associated with combustion (thermal NO_x). The formation of fuel NO_x depends on the nitrogen content of the fuel, total excess air rates, and relative distribution of primary and secondary combustion air. Thermal NO_x formation is determined by oxygen availability, temperature, pressure, and residence time in the combustion unit. The design and operation of combustion units and the fuel characteristics dictate the relative contributions of fuel and thermal NO_x . In turn, this determines which reduction techniques are suitable.

For example, thermal NO_x predominates in gas turbines because the primary fuel's nitrogen content is low. Therefore, controls for turbines aim to minimize peak flame temperatures and oxygen availability. But in municipal solid waste incinerators, reductions are achieved by favorable air mixing and distribution. In this case, emissions may be comprised of 75-80 per cent fuel NO_x .

Reducing Formation

Emissions can be reduced by modifications that limit their formation during high-temperature operations such as combustion. Reductions during combustion can be achieved by the use of low-nitrogen fuels and modifying design and operating features of the combustion unit. Modifications include flue gas recirculation, reducing the combustion air quantity (low- NO_x burners), and reducing flame temperature by prolonging the combustion time (staged-air combustion). These may be used individually or in combination.

Reduction after Formation

Generally, NO_x cannot be effectively scrubbed with conventional scrubbers. Trapping NO_x in a scrubber to form a weak nitric acid merely converts a solid waste into a liquid waste, accomplishing nothing unless a plant use exists for a weak acid solution. Removal of NO_x by aqueous scrubbing of a gas stream is difficult, requiring reduction with ammonia, either in a catalytic bed or at a high temperature. These methods, which are commonly used in glass furnaces, involves injection of ammonia into the hot flue gas in the presence or absence of catalysts and are referred to as selective catalytic reduction (SCR) and non-catalytic reduction, respectively. They are sometimes referred to as ammonia injection or ammonia reduction processes.

Ammonia Reduction

Ammonia is used in most of the catalytic systems as a reducing agent and under the proper conditions it will react selectively with NO_x in air instead of with the oxygen. Temperature is critical to the desired reaction. Above $1,100^\circ\text{C}$, ammonia reacts with the oxygen, below 850°C , ammonia will not react with the NO_x . Typical reductions with the SCR process range from 70 to 90 per cent and with the non-catalytic reduction process from 30 to 70 per cent. Note that catalyst manufacturers claim that many rich or lean burn power-generation facilities can now economically reduce nitrogen oxide emissions below 10 ppm with catalysts without handling ammonia or other difficult to manage reducing agents.

Ammonia reduction offers several advantages: 1) low cost, 2) presence of oxygen is not a problem, 3) excess ammonia is easily removed by a scrubber, and 4) presence of water in waste (salt form) is not a problem and appeared to be beneficial.

Selective Catalytic Reduction

SCR technology for the reduction of NO_x , SO_x , and CO, patented by Engelhard in 1959, was first commercialized in Japan and Japanese companies still dominate this market. The process is also widely used in Europe, particularly in Germany, in both large-scale utilities and in small-scale industrial boilers. At present, U.S. companies such as Engelhard, W.R. Grace (Davison Chemical Division and Camet Corp.), Radian Corp., and Ralph M. Parsons Co. are actively involved in the development and commercialization of SCR catalysts and processes.

SCR typically involves the injection of ammonia into the hot flue gas in the presence of catalysts. However, Radian Corp. is developing a system called Hybrid Low- NO_x that works without ammonia. It uses a precious-metal catalyst to reduce NO_x and simultaneously oxidize CO and hydrocarbons.

Although SCR systems have been used for a long time in Japanese and European power plants, these plants burn coal that is lower in sulfur ($<1\%$) than that burned in the U.S. This raises uncertainties about transferring this technology directly to the U.S. Because of this, the Electric Power Research Institute (EPRI) has done a feasibility study of SCR of NO_x and control of residual NH_3 and SO_3 in power-generating plants. The study evaluated six hypothetical power plants that were designed to burn high-sulfur coals. The designs were submitted to a major SCR equipment supplier for process and cost estimates.

The EPRI study outlines plans for a series of SCR pilot plants in the U.S., to be established at utilities that currently burn medium- and high-sulfur fuels. The designs included new

plants and retrofits, high- and low-sulfur coal, high-sulfur oil, pulverized coal and cyclone-fired boilers, and two common options for reactor placement: 1) hot side between the economizer and air heater and 2) cold side behind the flue gas desulfurization units.

Non-catalytic Reduction

Non-catalytic reduction involves the injection of ammonia into the hot flue gas in the absence of catalysts. This process is used in the U.S. in some small-scale industrial boilers.

Scrubbing

A problem for thermal technologies is that the scrubbing of NO_x is still partly science and some art. The lower oxides of nitrogen, which have a low aqueous solubility, are often not removed and need to be reoxidized and rescrubbed in many stages, only to produce another nitrate/nitrite-contaminated waste stream, possibly containing radioelements. Additionally, radioelements that become volatile in the temperature range of 588 to 1,200°C must be scrubbed out, thereby producing yet another separate waste stream.

A conventional method for removing NO_x emissions is limestone wet-scrubbing. However, dry scrubbing is another technology that shows promise for controlling these emissions. Dry scrubbing of stack gases with a dry sodium reagent (such as sodium bicarbonate) will remove both SO_2 and NO_x , supposedly at a cost far lower than that for conventional limestone wet-scrubbing systems. However, the plant must be retrofitted with the necessary silos and injection equipment. Table 31 lists the advantages and disadvantages of wet scrubbers.

The gases and airborne effluent generated by the Research-scale Melter Vitrification Process (PNL HWVP Technology Development Project) are exhausted through and treated by an off-gas system. An insulated 1-inch stainless steel tube is extended from the melter and is routed through a venturi scrubber to provide initial cooling and remove the majority of the condensable and particulate material. The liquid for the scrubber is recirculated in a continuous loop, which passes through a small shell-and-tube heat exchanger to remove the heat from the melter off-gas. As condensate accumulates, it is drained. From the scrubber, the off-gas is run through a High Efficiency Mist Eliminator (HEME). The HEME will remove condensed phase aerosols.

TABLE 31

ADVANTAGES AND DISADVANTAGES OF WET SCRUBBERS

ADVANTAGES

1. No secondary dust source.
2. Relatively small space requirements.
3. Ability to collect gases as well as particulates (especially "sticky" ones).
4. Ability to handle high-temperature, high-humidity gas streams.
5. Capital cost low (if waste water treatment system not required).
6. For some processes, gas stream already at high pressures (so pressure-drop considerations may not be significant).
7. Ability to achieve high collection efficiencies on fine particulates (however, at the expense of pressure drop).

DISADVANTAGES

1. Possible creation of water-disposal problem.
2. Product collected wet.
3. Corrosion problems more severe than with dry systems.
4. Steam plume opacity and/or droplet entrainment possibly objectionable.
5. Pressure-drop and horsepower requirements possibly high.
6. Solids buildup at the wet-dry interface possibly a problem.
7. Relatively high maintenance costs.

Source: *Perry's Chemical Engineers' Handbook*, 6th Ed., R.H. Perry, D. Green, J.O. Maloney, McGraw-Hill Publishing, New York, 1984.

RECLAMATION/REUSE

The use of a waste product from one unit operation as a portion of the feedstock for another process is an industry ideal (refer to Minimum Additive Waste Stabilization Project, p.70). In the nuclear material processing field, this is all the more desirable as the processing and disposal of waste require considerable time and expense. Reuse of materials was given impetus by the RCRA and by DOE/DP-0013, Department of Energy Plan for Recovery and Utilization of Nuclear Byproducts from Defense Wastes. However, given the composition and nature of the waste generated at nuclear material processing sites, this ideal is rarely possible.

EXAMPLES WITHIN DOE

Various methods exist for separating nitrates from waste solutions for use as a raw material. These separation methods include evaporation (acid wastes only), electrochemical ion exchange, and electrodialysis. The NAC/NAG/NAX process, which destroys nitrates and produces ammonia, offers the possibility of ammonia reuse and consumption of contaminated scrap aluminum that is currently stored on the DOE complex. Unfortunately, because water vapor is contained in the NAC/NAG/NAX off-gas stream, the economics of ammonia recovery do not look good.

A few examples where reuse is being practiced on a limited scale (i.e., reuse of the waste is confined to the plantsite where generated) are ammonium nitrate, aluminum nitrate, and nitric acid. Ammonium nitrate and nitric acid can be produced from ammonia. Ammonium

sulfate is also discussed here because it is a potential by-product from the NAC/NAG/NAX process.

Aluminum Nitrate

Recovery of aluminum nitrate has been an ongoing program at the Oak Ridge Y-12 Plant for several years. Industrial applications of aluminum nitrate include textiles (mordant), leather tanning, manufacture of incandescent filaments, catalyst in petroleum refining, nucleonics, anticorrosion agent, and as an antiperspirant.

Ammonium Nitrate

At the Kerr-McGee Nuclear Corp. (KMNC), the processed nitrate waste is a dilute (3-6% nitrate) aqueous solution of ammonium nitrate. This was recognized as an excellent fertilization agent and this use has been pursued by the company.

During the conversion of uranium oxide to uranium fluoride at KMNC, a neutralized raffinate of ammonium nitrate is generated. This has been pumped to a solar pond for storage and evaporation. The raffinate contains a <1 ppm concentration of uranium and, since the uranium has not been irradiated in a nuclear reactor, none of the transuranic radioisotopes are present. Recognizing the fertilizer potential in this material, KMNC included in their NRC license the testing of this material in on-site locations since 1973.

Preliminary testing was on small plots near the solar pond, with comparison to commercial nitrogen fertilization as to foliage growth, heavy metal and radionuclide accumulation in the soil, and water carry-off. The program has since expanded to over 3,000 acres of both timberland and pasturage, now under the control of a university agronomist. A small herd of cattle graze on the pasture land with no ill effects. Independent diagnostic laboratory findings have shown there is also no effect anywhere in the food chain.

An amendment to the operating license with the NRC allows use of the fertilizer on an unlimited basis, permitting the sale for off-site use. However, Kerr-McGee is responsible for analyzing the forage grown. This cost and the cost of shipping a solution containing only 3 to 6 per cent nitrate made the off-site sale uneconomical. Currently, KMNC uses part of the solution for on-site fertilization only, and the remainder is injected into deep wells.

Ammonium Sulfate

Ammonium sulfate is the 30th highest volume chemical produced in the U.S. Potential uses include fertilizers, water treatment, fermentation, fireproofing compositions, viscose rayon, tanning, and food additive.

Nitric Acid

Another recovery operation is the production of nitric acid from a dilute nitric acid stream used in a dissolution process. Recovery of nitric acid has also been an ongoing program at the Oak Ridge Y-12 Plant for several years. While this is not disposal or reuse of a nitrate salt, it does recycle the nitrate that would otherwise end up as a nitrate salt after waste neutralization.

Nitric acid also can potentially be produced from alkaline nitrate wastes by oxidizing the ammonia recovered from the NAC/NAG/NAX process. According to *Plant Design and Economics for Chemical Engineers*, 1 kg of ammonia (plus air and water) produces 5.7 kg of 61 wt.% nitric acid.

Separation methods are being examined at the Rocky Flats Plant for recovering nitric acid from acidic streams for reuse. If a use can be found for the recovered nitric acid, it may be desirable to remove nitrates from acidic mixed wastes rather than destroying them. For these waste streams, nitric acid can be reclaimed before they are processed and neutralized. The most common approach is to distill the acid from spent streams. In some cases, pre-treatment and post-treatment are required to remove specific contaminants that would be detrimental to future product performance.

By reclaiming from the high-acid streams, the amount of nitrate waste could be greatly reduced. If the processing cost of the reclaimed acid is compared with that of fresh acid, it will probably more expensive to produce than to buy fresh acid. However, a fair analysis must include the cost and consequences of handling and disposing the nitrate waste.

AMMONIA

Because ammonia is the most important, and practically the only, building block for synthetic nitrogen products worldwide, there are many potential applications for its reuse if it could be recovered inexpensively.

Applications and Market

Figure 2 shows the products that can be derived from ammonia and Table 32 lists the quantity of ammonia that is consumed (source does not specify whether U.S. or worldwide consumption) in the production of the various products. Table 33 lists the industrial uses of ammonia.

TABLE 32
AMMONIA MARKET

PRODUCT	1,000 SHORT TONS
Direct fertilizer application	4,880
Urea	4,230
Ammonium phosphates	3,150
Nitric acid, industrial	2,300
Ammonium nitrate	1,600
Others	1,300
Acrylonitrile	600
Ammonium sulfate	600
Total	18,710

Source: *Riegel's Handbook of Industrial Chemistry*, 9th Ed., James A. Kent, Van Nostrand Reinhold, NY, 1992.

SYNTHETIC NITROGEN PRODUCTS

Fig. 2. Synthetic nitrogen products.

TABLE 33
INDUSTRIAL USES OF AMMONIA

INDUSTRY	USAGE
Explosives	Nitrates, dynamite, azides
Plastics	Nitrocellulose, urea-formaldehyde, melamine, methylmethacrylates, paints
Metallurgy	Bright annealing of steel, dry reducing gas
Pulp and paper	Ammonium bisulfate, melamine
Rubber	Aniline, acrylonitrile, polyurethanes, chemical blowing agents (for foam rubber)
Textiles	Nylons, acrylonitrile, terephthalates
Foods	Amino acids, sodium nitrite, and nitric oxides
Drugs	Vitamins, nitrofurans, nitrous oxide
Miscellaneous	Refrigerant, detergents, insecticides, nitroparaffins, hydrazine, air pollution control

Source: *Riegel's Handbook of Industrial Chemistry*, 9th Ed., James A. Kent, Van Nostrand Reinhold, NY, 1992.

Worldwide, the production of ammonia exceeds 265 billion pounds with 85 per cent of production used for fertilizers and the remainder going to all other uses. Of current world capacity—140 million short tons—70 per cent is based on natural gas, 6 per cent on plants partially converted from oil to natural gas, 10 per cent on naphtha and fuel oils, 4 per cent on by-product gases from coke ovens or refinery gas, and 10 per cent on coal. In the future, coal is expected to become of increasing importance as natural gas supplies are consumed and natural gas prices escalate.

History

Prior to World War II, ammonia production capacity remained relatively stable. During the war, the need for explosives caused an increase in the production of ammonia for nitric acid manufacture. Then, after the war, available ammonia capacity was directed to the manufacture of fertilizers.

Since 1963, there has been a revolution in ammonia-manufacturing technology. The advent of large single-train plants has resulted in a large increase in production capacity, the shutdown of a number of smaller plants, and a reduction in manufacturing costs. The total capacity of U.S. ammonia producers in 1990 was estimated to be 15.5 million metric tons per year.

Storage and Transport

Ammonia usually is stored in large 20,000-ton atmospheric-pressure tanks at a temperature of -28°F. With this system, the ammonia vaporized by heat in-leakage must be compressed and condensed, and then returned to the system. Some of the low-pressure tanks are built

with a double wall; this adds some protection against leakage and also provides a means for retaining insulation.

Normally, ammonia is transported by barge, ship, or tank cars to terminals located at strategic points in the consuming agricultural areas. Some ammonia is transported by interstate pipelines.

Price and Process Licensors

List price for ammonia, f.o.b. Gulf Coast in tank cars was reported at \$110/short ton in the April 1991. In May 1994, the price of aqueous ammonia (29.4%) is listed at \$260/ton. The price of ammonia follows energy prices very closely and can vary by as much as \$30 over short periods of time. The price of ammonium nitrate (May 1994) is listed at \$150-155/ton. The price of ammonium sulfate (May 1994) is listed at \$85-105/ton for carload quantities of large granular material, \$132/ton for car- and truck-load quantities of technical grade in bags, and \$38-45/ton is the standard commercial bulk rate. Licensors (as of 1990) for ammonia plant technology are listed in Table 34.

TABLE 34
AMMONIA PROCESS LICENSORS

Ammonia Casale	M.W. Kellogg
Bechtel	KTI
C.F. Braun	Linde
CECP	Lurgi/Shell
ChemieLinz/Chemserv	Nippon Kokan
Fish	Polimex-Cekop
Haldor Topsoe	Pritchard
Howe-Baker	Quimigal
ICI Chemicals	Uhde

Source: *Riegel's Handbook of Industrial Chemistry*, 9th Ed., James A. Kent, Van Nostrand Reinhold, NY, 1992.

Control Technology

According to R.M. Counce (DRAFT: *Estimated Capital and Annualized Operating Costs for Off-Gas Processing Systems for Application of the NAC Process and a Conceptual Thermal Decomposition Process to the Treatment of Nitrate-Based Aqueous Wastes*), the choice of control technology for ammonia depends upon the control objectives. These objectives may involve treatment to convert ammonia to less hazardous materials or recovery and reuse. Treatment technologies based on oxidation to N_2 and H_2O are given more treatment by Counce although reaction with a strong acid to produce an ammonium salt was also discussed. Recovery technologies based on condensation and aqueous absorption/stripping operations are typically used in industry and are also discussed by Counce. Note, however, that the use of condensation is limited due to the water vapor in the off-gas.

The major options for control of gaseous ammonia are (1) condensation, (2) catalytic oxidation, and (3) absorption into an acidic aqueous solution. Ammonia is easily condensed from gas stream although it is typically removed industrially by aqueous absorption.

Control of gaseous ammonia by catalytic oxidation is not common in industry but may become more common as regulation becomes more stringent. Ammonia is commonly used industrially as a reductant for control of gaseous NO_x. Ammonia should be readily adsorbable due to its polar nature. However, there has been little interest in studying the adsorption of ammonia except in regard to catalytic reactions. Ammonia is commonly removed from gas streams by absorption and reaction with sulfuric acid, which results in the production of (NH₄)₂SO₄.

The low boiling point of ammonia is an indication of the ease by which it may be recovered by condensation (if water is not present). One commercially available cryogenic vapor recovery system provides a stream reasonably free of ammonia and a liquid stream of condensed ammonia. Such a process could provide a source of ammonia for local use such as a selective catalytic reduction system for NO_x control or its catalytic oxidation to N₂ under carefully controlled conditions.

Examples of recovery and reuse of ammonia may be found in the Andrussov process for HCN production, the Solvay process for sodium carbonate production, typical processes for the production of diammonium phosphate and superphosphate, as well as for coke production facilities. An example of such a recovery process is the PHOSAM process developed by U.S. Steel Corp. After reaction with NH₄H₂PO₄ (l), the ammonia is recovered in a separate vessel by steam stripping.

FINAL WASTE FORMS

Information presented in this chapter was obtained from the following sources:

1) *Radioactive Waste Forms for the Future* and 2) *Technical Area Status Report for Low-Level Mixed Waste Final Forms* (DOE/MWIP-3, Aug. 1993).

WASTE-FORM SELECTION

During the period from 1977 to 1982, many different types of nuclear waste forms were evaluated for U.S. defense waste (high-level waste streams arising from the U.S. weapons program). The decision was made to use borosilicate glass as the waste form at the Defense Waste Processing Facility (DWPF) at Savannah River. SYNROC, a titanate-based ceramic, was selected as the alternative waste form. Further development for high-level waste forms ended in the U.S. when borosilicate glass was selected as the waste form for the DWPF. Major R&D programs for SYNROC continued in Australia with collaborative projects in Japan and Great Britain.

Early Comparisons

Waste form comparisons from the 1977 to 1982 period are summarized, in part, in the three reports (Hench et al. 1979, 1980, 1981) of the Alternative Waste Form Peer Review Panel of the Department of Energy. The final conclusions are summarized in Hench et al. (1984). A description of the final evaluation process, performance indices, weighting factors, processing factors, and selection criteria used for defense waste are summarized by T.A. Bernadzikowski in *The Evaluation and Selection of Candidate High-level Waste Forms* (Report No. USDOE/TIC-11611, 1982).

In these early comparisons, radionuclide transport behavior calculations showed that differences in the performance between waste forms (e.g., glass versus ceramic) did not result in significant differences in the final "dose-to-man." However, these calculations did not take into account the various processes by which a waste form might degrade (e.g., fracture, corrosion, or radiation effects).

Recent Comparisons

The editors of *Radioactive Waste Forms for the Future* do not believe that the simplified comparisons of the past are useful or applicable to the long-term behavior of nuclear waste forms. They feel that a simple comparison of leach rates under standard conditions is irrelevant to long-term extrapolations of waste-form corrosion. The proper comparison requires a careful consideration of leaching mechanisms and important parameters that can change a given mechanism such as corrosion and radiation effects.

Unfortunately, it appears that there can be no simple comparison of waste forms. The editors of the above-mentioned book indicate that the study of corrosion processes using standard tests provides little basis for the comparison of long-term behavior. Corrosion tests must be repository specific and be designed to obtain a fundamental understanding of the corrosion and radionuclide release mechanism. In the absence of an understanding of the mechanism, little can be said concerning the long-term behavior. If possible, predicted long-term behavior should be verified by the study of natural analogues.

WASTE-FORM CRITERIA

Table 35 provides a summary of significant tests that must be met by all stabilization methods, regardless of the final waste form.

TABLE 35
STABILIZED WASTE CHARACTERISTICS AND TEST
REQUIREMENTS

CHARACTERISTIC	TEST REQUIREMENT
Leach resistance	TCLP: 40 CFR 61 ANSI/ANS - 16.1, 1986, Section 2.0 PCT: Product Consistency Test MCC-IP and/or MCC-3
Durability	Freeze/thaw Cycles, 30 cycles at 40-85°C, ASTM B553 Compressive Strength, >500 PSI Unconfined Wetting/drying Cycles
Biodegradation	Fungi Attack, ASTM G21-70 Bacterial Attack, ASTM G22-76
Other	Radiation Resistance, 1 million Rads, Integrated Free Liquid, Less than 0.5% Volume, Freestanding

Source: *Modular Enviroglass™ Vitrification Technology for Low-Level Radioactive and Mixed Wastes*, J. Bradley Mason, VECTRA Technologies, Inc., VECTRA Document No. SP-5010-01, Rev. 2, May 1994.

WASTE-FORM CHOICES

Some thirty years of world-wide effort has gone into the preparation of practical schemes for waste immobilization in borosilicate glass, including the building and operation of fully engineered melters for remote (hot cell or canyon) production of radioactive glass. Consequently, the technology involved is well understood. As a result of this effort, there is a tremendous momentum behind the borosilicate glass programs in many countries.

However, in Canada, since there is no immediate need to decide on any one route for nuclear waste disposal, there is a greater freedom within the program to explore alternative methods and materials for waste immobilization. Three classes of materials are under development in the Canadian program as possible media for fuel recycle waste solidification: borosilicate glasses based on $\text{Na}_2\text{O}-\text{B}_2\text{O}_3-\text{SiO}_2$ compositions, aluminosilicate glasses based on $\text{Na}_2\text{O}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ compositions, and sphene-based (i.e., titanate) glass ceramics (Dixon and Rosinger 1984, Hancox 1986).

There are many waste forms that have been evaluated in the U.S. for high-level waste disposal, but the two most prominent are borosilicate glass and SYNROC. Other materials include sintered glass, lead-iron-phosphate glass, tailored ceramics, titanate, glass ceramic, monazite, and FUE-TAP concretes. Materials that are considered novel include high-silica, porous glass matrix, sodium zirconium phosphate, and low-temperature hydroxylated ceramics.

Glass compositions always reflect a compromise between glass durability and technical feasibility of the glass as well as economic considerations. According to the editors of *Radioactive Waste Forms for the Future*, the decision to use borosilicate glass as the waste form for defense high-level waste was based in part on the recommendation of a review panel (Hench et al. 1979, 1980, 1981). On behalf of the DOE, the panel reviewed the state of the art in the fields of R&D processing experience, and of the waste forms reviewed, borosilicate and SYNROC received the highest ranking out of eight alternative waste forms. The sequence of ranking in decreasing order of preference was: borosilicate glass, SYNROC, porous glass matrix (high-silica glass), tailored ceramics, pyrolytic C and SiC coated particles, FUE-TAP concrete, metal matrices, and plasma spray coatings.

Proponents of ceramic or crystalline waste forms have stressed the inability of glasses to reach a saturation equilibrium with ground waters (because of their inherent thermodynamic instability with respect to crystalline reaction products). They also claim that glasses show more sensitivity to temperature change in their rates of reaction with water than ceramics. The use of ceramic counterparts to natural mineral assemblages as waste forms allows estimates of waste-form behavior in many geochemical environments to be made from studies of the weathering and alteration of the mineral assemblages. Studies of metamictization in minerals could be used to predict the susceptibility of ceramic waste forms to radiation and transmutation damage, which would otherwise be difficult to simulate because of the long time intervals involved.

Proponents of silicate glasses indicate that the long-term stability, i.e., resistance to weathering and chemical attack, can be supported by archeological evidence. Artifacts (e.g., worked obsidian and medieval glasses and basalt glasses) have been used to predict long-term chemical durability and to verify calculated corrosion rates for silicate glasses.

Partly as a result of these criticisms of glasses, the design criteria for a high-level waste vault have been significantly revised. In particular, extended cooling periods for the spent fuel and/or fuel recycle wastes are now specified, in order to reduce the temperature

excursion within a vault that would occur after waste emplacement and vault closure. With these new criteria, borosilicate glasses remain the preferred choice for a first-generation waste-form material for most national programs.

Non-crystalline

Non-crystalline or amorphous waste forms (i.e., glasses) are normally obtained by mixing one or more waste streams containing radioactive and hazardous inorganic chemical compounds with glass-forming materials and melting during a vitrification process. The glass forming materials may be commercially melted glass frit, select chemicals, or in some cases, materials that are present in the waste streams. Glasses are not composed of discrete molecules, but are three-dimensional, continuous networks.

While glasses often exhibit high chemical durability, and have been found in nature with ages of millions of years, they are thermodynamically unstable with respect to conversion to crystalline forms of the materials of which they are composed. Given extended times at elevated temperatures [above about 450-500°C (842-932°F)] or contact with water over long periods, they will convert to crystalline minerals.

Glass may be formed by thermal processes or by non-thermal processes such as vapor deposition, solution hydrolysis, or gel formation. Thermally formed glasses are produced by fusing or melting crystalline materials and/or amorphous materials at elevated temperatures to produce liquids, which are subsequently cooled to a rigid condition without crystallization. Many waste glasses also have one or more crystalline phases distributed in the glass.

Materials that have been evaluated as a waste form include silicate glasses, such as borosilicates ($\text{B}_2\text{O}_3\text{-SiO}_2$), aluminosilicates ($\text{Al}_2\text{O}_3\text{-SiO}_2$), and sodalime silica ($\text{Na}_2\text{O-CaO-SiO}_2$), and phosphate (P_2O_5) glasses. However, most glasses are based on the silica network.

Silicate Glasses

The glass waste form discussed in the vast majority of references is borosilicate glass and is used in the high-level waste program. The waste form usually contains less than 30 wt.% of waste solids and the vitrification process generally reduces the waste volume significantly.

Silicate glasses have long been the preferred nuclear waste form because they readily accept a wide range of waste stream compositions; can easily be modified by additives to optimize physical and chemical properties; and vitrification is a demonstrated large-scale process. An important difficulty with waste forms has been the need to adjust compositions (usually by lowering the silica content) so that processing temperatures are lowered to prevent melter corrosion and so that viscosity is well within an optimal processing range. Lowering the waste loading in the glass would increase the product quality, but this also increases the number of canisters produced, which is economically less desirable.

Composition

The range of chemical compositions for today's borosilicate nuclear waste glasses is determined by the processing technique, e.g., formation temperatures, viscosity, electrical resistivity, and waste composition.

The compositional changes (decreased silica and increased content of network modifying elements) necessitated by these processing requirements have resulted in glasses that are less durable than higher silica glasses. However, some work has shown that it is possible to produce a radionuclide-containing high-silica glass that provides greater chemical durability. Ideally, the chemically most durable glass waste form is vitreous silica with a small amount of the waste oxides heterogeneously dispersed or homogeneously dissolved at high dilution in the SiO_2 network. To realize this type of glass waste form, the porous glass matrix concept was developed.

A high-silica waste form cannot be produced by melting because the melting temperatures are too high, $\geq 1,700^\circ\text{C}$. Several highly radioactive fission products, including cesium, ruthenium, technetium, selenium, sulfur, and fluorine, would almost quantitatively be volatilized instead of being incorporated in the glass matrix. Inactive constituents of the waste, such as alkali oxides are volatile and clog the off-gas system. Therefore, in a melting process, glass formation temperatures must be in the range of $1,150$ and $1,200^\circ\text{C}$. Glass formers other than silica must be added to lower the melting temperature of silica. Highly viscous silica-rich glass melts (>150 dPas at $1,150^\circ\text{C}$) require extended residence times in the melter, lower the throughput, and increase plant operating costs.

The high-silica, porous glass matrix (PGM) developed at Catholic University involves a process in which a homogeneous glass is phase-separated into high-silica and low-silica regions. The phase-separated glass is preferentially dissolved in an acid solution that does not attack the high-silica regions. The resulting glass has an interconnected porous structure and pore sizes in the range of 10 to 50 nm and consists of 96 wt.% SiO_2 and 4 wt.% B_2O_3 . The radionuclides are incorporated in the PGM by soaking in the liquid wastes. The "loaded" PGM is then cleaned with a solvent to remove waste material salts from the outer surface and slowly dried up to temperatures of 700°C to remove water and decompose the waste to component oxides. Sintering at 900°C collapses the structure by viscous flow and seals the waste in a high-silica envelope. By varying the processing parameters, the high-silica envelope can be made to any thickness.

Borosilicates. Boron oxide has become the commonly used substitute for silicon. At low temperature (500 - 600°C) boron stabilizes the glass structure by forming BO_4 groups. Often boron has a beneficial effect on the chemical durability of glasses, and this property has been widely used by glass industries in the manufacture of corrosion-resistant glasses. At high temperatures, boron becomes a network modifier, thereby lowering the melt's viscosity. Some findings give evidence that boron can help to stabilize certain elements in the glass phase.

There is a large database by which to evaluate performance under various repository conditions. The limits of application are well known (e.g., maximum waste loading and exposure of the waste form to fluids at elevated temperatures) and repository-related performance analyses have been completed. Criticisms in the scientific literature of the durability of borosilicate glasses (e.g., McCarthy et al. 1978, Ringwood 1978, Roy 1979) led to an international search for improved waste form materials.

The corrosion mechanism is well understood and extrapolated long-term behavior can be validated by observation of alteration phenomena of natural glasses. There are volcanic glasses that have been exposed to long-term alteration in nature (up to 10^7 years) that have been studied as natural analogues for borosilicate nuclear waste glasses in order to verify predictions obtained from short-term tests in the laboratory.

Borosilicate-based glass is the only nuclear waste form that has been produced on a large scale using the vitrification process. The basic glass system for most of the HLW glass formulations is the ternary system $\text{Na}_2\text{O}-\text{B}_2\text{O}_3-\text{SiO}_2$. An alternative technique for the fabrication of borosilicate glass at lower temperatures, sintering, has been developed and tested and can be adapted for "hot" operation.

Industrial-scale fabrication has been demonstrated and production experience has been acquired in a number of countries. A total of over 500 tons of highly radioactive glass have been produced from liquid reprocessing wastes in France and in Germany. The U.S. has built processing facilities at the Savannah River Defense Plant (Defense Waste Processing Facility, DWPF) and the West Valley Reprocessing Plant (West Valley Demonstration Project, WVDP). There are plans to build facilities at the Hanford Defense Plant and at the Idaho Chemical Reprocessing Plant. DWPF is expected to produce 6,500 canisters, 410 per year (0.60 meters in diameter and 3 meters high) and WVDP 300 canisters of the same size.

Aluminosilicates. The dissolution of aluminosilicate glasses containing active HLW (the "Chalk River Glasses") has already been the subject of considerable study (Merritt 1976, Melnyk et al. 1984, Tait et al. 1986). The results have shown the glasses to be significantly more durable than typical waste-containing borosilicate glasses, usually by one or two orders of magnitude. This fact, which has been confirmed by Tait and Mandolesi (1983), was a major reason for the original inclusion of Al_2O_3 (rather than, say, B_2O_3) in the formulation of a sphene glass-ceramic. Literature also indicates that high aluminum glasses are leach resistant and lower the volatility of Cs as compared to other glasses.

There are some disadvantages of alkali aluminosilicates glasses. They have relatively high viscosity so higher process temperatures are required for flowable product. Adding fluxing agents to reduce process temperature lowers waste loading. Additions of B_2O_3 lowered viscosities, but some phase separations were observed. Crucible trials have been initiated in order to identify promising glass formulations for the NAG waste form.

Chemical Durability

A large number of critical variables have been investigated in the analysis of the corrosion process. These include: glass composition, pH in the leachate, chemical composition of the leachant, redox potential, flow rate, temperature, waste package materials, and the formation of surface layers. The database describing these experiments is extensive and important conclusions are:

- Different glasses have different corrosion rates. The corrosion rate can be related to the free energy of hydration of the glass.
- The corrosion rate decreases with time in a closed system by several orders of magnitude, relative to its initial value.
- The corrosion rate is constant in flowing water if transport through surface layers is not rate controlling. The corrosion rate is typically on the order of 0.5 to 5.0 g/m²-d, at 90°C. There is experimental evidence, as well as evidence from *in situ* experiments and from

natural glasses, suggesting that glass corrosion continues at a low rate, on the order of 10^{-3} g/m-d or less, over long periods of time, even in closed systems.

- Solid reaction products form as layers on the surface of the pristine glass. These layers, which may contain elements from the glass and from solution, consist of crystalline and non-crystalline phases ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$, analcime, with Al and Si from the glass, Na and H_2O from an NaCl leachant solution).

Radiation Effects

Radiation effects have a limited effect on the chemical and physical integrity of borosilicate nuclear waste glasses. Changes in density are small ($\pm 1\%$ or less) and stored energy is small (<150 J/g). Helium (from α -decay) is not released at temperatures $<50^\circ\text{C}$, but does not affect the chemical durability of the glass. Structure changes of crystalline phases, as a result of self-irradiation in the glass, may be major, but these phenomena have a negligible effect on the bulk waste form performance. Nuclear transmutations have no measurable effect on chemical durability. The influence of beta and gamma radiation on the chemical durability is reported to be smaller than that of alpha-decay. Alpha-decay decreases the chemical durability by a factor of ≤ 3 . There is a modest effect of radiolysis of water and gaseous species, nitrogen in particular, on the chemical durability, but the enhanced corrosion is less than a factor of 5.

Previous Research

Eliassen and Goldman (1961) reported on research work conducted at MIT to prepare glasses from synthetic wastes originating from aluminum, stainless steel, and zirconium-clad fuel elements. The wastes were spiked with radionuclides such as Cs-137 and Sr-90. Glass compositions consisted of Al_2O_3 , CaO , SiO_2 , B_2O_3 and Li, Na, K oxides substituted for CaO . Effect of high radiation doses on glass durability was practically unknown and was, therefore, given much attention. The glasses, which were subjected to high gamma doses, showed no significant decrease in chemical durability. The same result was obtained by Grover and Chidley (1960).

At Idaho National Engineering Laboratory (INEL), a fluidized-bed calcination process originally conceived at Argonne National Laboratory (Jonke et al. 1957) was developed (Buckham and McBride 1963) to convert high-level liquid aluminum-rich waste to solids. However, efforts have been made to prepare chemically more durable waste forms than calcines. Among these were silicate and phosphate glasses in combination with borates, the exact composition depending on the particular waste composition. In many cases, laboratory-scale or larger-scale preparation processes were designed and tested (Clark and Godbee 1963, Hatch et al. 1963, Barton 1961, Eliassen and Goldman 1961, Platt and Schefcik 1961, Tuthill et al. 1961). The development of vitrification processes became increasingly significant in the 1960s with phosphate-based waste forms, as ceramic products or glasses.

Phosphate Glass

The production of phosphate-based glass has been abandoned in the western world. Only in the Soviet Union are these glasses still being developed. Compared with silicate-based glasses, phosphate glasses have some advantages. They have a higher solubility for SO_4^{2-} ,

and lower formation temperatures (i.e., less radioactive material was evaporated, thereby reducing off-gas treatment problems).

However, the following are some major disadvantages with phosphate glass that were reported in 1972: high corrosivity of the feed solution, requiring the use of a platinum crucible as a melter, and most importantly, the observed devitrification of the phosphate glass and its deleterious effect of the glass, chemical durability (a factor of 1,000 decrease compared with the non-crystallized material. Today there are, however, other phosphate compositions for which devitrification is not such a major problem and which exhibit high chemical durability, at least in water (Sales and Boatner 1984).

Crystalline

Ideally, mineral phases can be identified and generated for each waste species, but this may not prove feasible and some species may be encapsulated or limited to grain boundaries. One advantage of this waste form is its thermodynamic stability. The amorphous calcium silicate hydrate matrix of cementitious waste forms is thermodynamically unstable, although it may last for millennia in dry environments. Glass is a supercooled liquid. Ceramics are dense mineral phases, thermodynamically stable.

As with glass, ceramics can be made with low porosity, making them less leachable than cementitious waste forms. As with cementitious waste forms, the chemical phases have low solubility, potentially making them less extractable than glass waste forms. Species relegated to grain boundaries, or physically encapsulated, may be just as extractable as before treatment. TCLP testing of specific waste forms is needed to verify this chemical stability. This technique is in its infancy.

Some wastes are ready made for conversion into ceramics, whereas others may require significant chemical conversion. The waste must not only be characterized as to elemental species, but also chemical species. This is a high-temperature technique with thermal destruction of organics, but may not be amenable to some volatile and semi-volatile species, such as mercury, tritium, iodine, cesium, and technetium.

Proponents of ceramic waste forms have stressed the inability of glasses to reach a saturation equilibrium with ground waters (because of their inherent thermodynamic instability with respect to crystalline reaction products). Researchers have shown experimentally that many crystalline waste form materials show less sensitivity to temperature change in their rates of reaction with water than do glasses.

Hydraulic Cement

Portland cement and similar materials (hydraulic cements) are the solidification agents most often referenced in available LLW solidification literature. The hydraulic cements can exhibit physical encapsulation and/or chemical bonding characteristics. These are dependent upon the cementing agent, water content, and waste stream involved. A list of hydraulic cement base agents is presented in Table 36.

TABLE 36
CEMENT-BASED WASTE-FORM SOLIDIFICATION MATERIALS

Portland cement	Type I - general use
	Type II - general use plus moderate sulfate resistance
	Type III - high early strength
	Type IV - low heat of hydration
	Type V - high sulfate resistance
	Plug - early set, expanding cement
	Masonry - high workability (highly alkaline)
Gypsum cement	Plaster of Paris
	Envirostone®
Grout (variable)	---
Slag cement	---
Polymer-modified cement	Latex cement
	Polymer-impregnated cements (concretes)
	Epoxy-cement mixtures or combinations
	Polymer-cement mixtures or combinations
Other	Alumina-based cement
	Silicate cement
	Lime or lime-fly ash mixtures
	Pozzolan cement

Source: *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

Portland Cement

Hydraulic cements include the general portland cement concretes (PCC) comprised primarily of calcium silicate species. These cements mix with water to form a basic slurry exhibiting an initial pH of 11 to 14, depending on the type of mix. Masonry cement contains free lime in addition to the portland cement component and is the most basic of the cements. Portland cements readily combine with most neutral and basic pH materials to produce a strong monolithic product. Strongly acidic waste components require at least partial neutralization prior to solidification. The cements, particularly masonry cement, are inherently basic and can be used to neutralize and solidify some acidic materials in a single step.

Gypsum Cement

Gypsum is a calcium sulfate mineral. Plaster of paris is a typical gypsum cement and has 0.5 mole water per mole of reagent. It reacts with water to form a gypsum-type compound (calcium sulfate with two moles water per mole of reagent). Plaster of paris has a neutral pH when mixed with water. It can be used to immobilize ammonium salts, and it encapsulates the salt or the dissolved liquid in its neutral matrix. The ammonium ion is stable (does not decompose) in the neutral matrix and the mixture solidifies without the loss of any appreciable ammonia gas. It will solidify other neutral and moderately acidic or basic compounds without affecting the general gypsum product characteristics. Gypsum typically sets faster than portland cement, but produces lower strength products.

Grout

Grout is a pumpable mixture containing a cement base and other materials, such as clay and flyash, to increase radionuclide or hazardous chemical retention. Grout contains more water and solidifies more slowly than the typical portland cement. Mechanical strengths such as compressive strength are typically lower for grout than for cement. Grout is used to provide higher waste loadings and better waste retention properties and is designed for pipeline delivery or transport.

Slag Cement

Slag cement (blast furnace slag cement) is a by-product of the steel industry. It is a high-temperature fired material and looks much like fly ash. Unless being used directly to solidify highly caustic materials, it requires an initiator (caustic-type compound), generally portland cement or lime. Its solidification time and other characteristics are very similar to those of cement. It has been shown to exhibit better waste retention properties and leach performance than similar portland cement products, but generally exhibits lower strength.

Polymer-modified Cements

Portland cement products, being naturally basic, are susceptible to degradation by acids and to a less extent by certain salts. This is true in applications such as concrete tanks, floors, and buildings. Cement in these applications can be modified with polymer materials to seal it and make it less penetrable. This type of treatment can be used to reduce water penetration and reduce leachability. Polymer modified cement waste products are expected to exhibit improved leach performance, better waste retention properties, and even better physical strengths. Polymer-modified cement can be used to achieve many of the positive characteristics of organic polymers and is still fire resistant, since the bulk of the matrix is non-flammable.

Other

Other hydraulic cements include pozzolan cement, which is portland cement base material (~75%) with an added pozzolanic material (25%) such as volcanic ash. It can exhibit higher compressive strengths and sometimes better waste retention than some of the other cements, and it is generally not as basic. Since pozzolan cement already has ash in it, it should not be used for immobilizing ash waste; conversely waste ash can potentially be blended with portland cement to make a pozzolanic material that could be used to solidify other mixed waste materials.

Alumina cements are also available. These exhibit the best fire protection properties of the hydraulic cements, have different material compatibilities (sometimes better), and generally have lower waste loadings. The alumina cements are usually more expensive and less commonly available. Also, lime and other natural cements are available. They are used for special purposes or applications. They are generally used when the more common cements are not compatible with the waste matrix. Lime and other natural cement products exhibit lower compressive strengths than portland cement.

Sulfur Polymer Cement

Sulfur polymer cement (SPC) and modified sulfur cement are different names for the same substance, which consists of 95 wt.% sulfur, 2.5 wt.% dicyclopentadiene, and 2.5 wt.% oligomers of cyclopentadiene. The phrase "modified sulfur cement," however, has been dropped by the industry. Sulfur polymer cement in its original flaked cement form, in its molten form, in its molten form with waste added, and in its final solid concrete form are all referred to as SPC. A different formulation of 'SPC' is commercially manufactured in Canada under the tradename Sulfurcrete®, but it has not yet been investigated and is not included in this discussion.

SPC is available commercially under the tradename Chemet 2000®. Because of SPC's unusual physical and chemical properties, DOE and the Commission of European Communities began testing and developing SPC as a solidification and stabilization agent for radioactive and hazardous wastes.

SPC is a thermoplastic ceramic that starts softening at 110-115°C (230-239°F) and starts melting at ~120°C (248°F). It reaches optimum pour consistency at 135°C (275°F) with a viscosity of 0.025-0.050 Pa-s (25-50 cp), roughly equivalent to cold automobile engine oil. It has a maximum safe operational mixing-and-pouring temperature of 150°C (302°F). Upon cooling, SPC with normal construction aggregate, achieves a strength of ~27.6 MPa (4,000 psi) and within two years has a strength of nearly three times that. When solid SPC is subjected to sustained high temperature, it will become molten again and then regain its strength upon cooling, as it did during the initial heating-cooling process.

SPC will not tolerate water in the mix; when water is in the waste, steam vents are formed in the concrete and it is weakened. For this reason, a waste product to be solidified should be heated to as much as 200°C (392°F) to evaporate the water. That heat is not wasted because it is used to help raise the SPC to pour temperature when the two are combined.

By U.S. Department of Transportation (DOT) and United Nations (UN) standards, solid SPC is not flammable. SPC will not support combustion. If a torch is directed to its surface, SPC will burn and form a self-extinguishing black char that puts out the flame. Any time the torch is removed, the flame will self-extinguish. During pouring operations, normal safety procedures will prevent any flammability or explosive condition.

Linear shrinkage is 0.1 per cent, slightly greater than that of PCC. SPC is a durable high-strength concrete that is resistant to abrasion and to attack by most acids, salts, and sulfates that destroy hydraulic concretes. It is advantageous to use where exposure to high concentrations of mineral acids, corrosive electrolytes, salt solutions, or corrosive atmospheres in general is expected.

Ceramics, Glass-ceramics, and "Chemically Bonded" Ceramics

In American usage, the term "ceramic" refers to any of a class of inorganic non-metallic products that are subjected to a high temperature during manufacture or use. This definition includes crystalline ceramics, glass, and glass-ceramics, which are composed of crystals within a glass matrix. "Ceramic" also includes the so-called chemically bonded ceramics that are manufactured at lower temperatures, but can be used at high temperatures. These materials are formed by chemical bonding at low temperatures as opposed to the high-temperature sintering or fusion of conventional ceramics. The most common process used for crystalline ceramic waste forms have been either hot pressing, or cold pressing and sintering of powders.

In designing a ceramic waste form, it is desirable to choose a chemically durable crystalline phase or phases that will incorporate the radionuclides within the crystal structure. However, there are certain constraints: 1) the overall composition of the waste stream, including non-radioactive components; 2) the desire to minimize the total waste form volume and thus the need to use high waste loading; and 3) the dictates of crystal chemistry and thermodynamics in determining the solubilities of the radionuclides in the various phases and the compatibility of the phases with each other during the high-temperature fabrication step.

Approaches to developing ceramic waste forms have thus varied in the degree to which they have attempted to direct the radionuclides into durable phases of the ceramist's choosing or, alternatively, to attempt to modify the waste stream composition by augmenting it with minimum amounts of additives, and thereby form phases that may not be as chemically durable (but still satisfactory) in order to achieve higher waste loading. An example of the former approach is titanate-based SYNROC. An example of the latter is tailored ceramic, which can achieve a waste loading of up to 85 per cent.

Principal among the ceramic waste forms that have been developed are supercalcine and tailored ceramics. Single phase (sodium zirconium phosphate, SZP) and low temperature (hydroxylated ceramics) have also been proposed.

The main advantages of **single-phase** ceramic waste forms are: (1) elimination of the need to make the tedious determinations of radionuclide partition coefficients between phases, (2) elimination of concern for differential mechanical properties (e.g., cracking caused by the different coefficients of thermal expansion or variations in volume changes that result from anisotropic radiation damage effects), (3) simpler modeling of corrosion mechanisms, (4) a potentially higher level of waste loading (e.g., compared to the dilute solid solutions used in SYNROC) and (5) a simpler technology for processing and quality control. These same advantages apply to the monazite nuclear waste form.

Advantages of the **low-temperature, "hydroxylated" ceramic** waste forms are: (1) low processing temperatures, (2) efficient radionuclide retention due to the sorptive properties of clays, and (3) the fact that most of the phases in the assemblage are hydroxylated and in thermodynamic equilibrium with typical alteration environments.

The hydroxylated ceramics can be considered to include almost any low-temperature, hydrated-phase assemblage (e.g., clay and zeolite assemblages; clay ceramics; concrete). Clays such as montmorillonite and kaolinite have been proposed for the fixation of radionuclides into crystalline phases. Waste (up to 50 wt.%) has been mixed with clays and sintered at temperatures up to 950°C to make a "clay-ceramic." It has been proposed that phase assemblages with low solubilities (mica, apatite, pollucite-wairakite, sodalite-cancrinite, and nepheline) be used for high-level commercial waste. Production of such waste forms will inevitably require low-temperature hydrothermal techniques, probably not dissimilar to those used in the production of waste form concretes. Work on these low-temperature phases as hosts for radionuclides has been completed in relation to their presence in low-level concrete waste forms.

Among the possible crystalline ceramic materials, those that have received the most study as host materials for radionuclides have been the oxides. Four main classes of crystalline-oxide ceramic waste forms have been developed: silicate-based, aluminate-based, phosphate-based, and titanate-based. Limited efforts to develop chemically bonded and glass-ceramic waste forms have also been conducted.

Silicate-based Ceramics

The most developed silicate-based ceramic waste form was called Supercalcine and was developed by McCarthy and co-workers at Penn State. Supercalcine formulations included such phases as pollucite, scheelite, fluorite, apatite, baddeleyite, corundum, spinels, and perovskites. They were formed by firing at temperatures over 1,000°C (1,832°F) with high oxygen partial pressures. This led to concerns about volatilization of elements such as Cs, Tc, and Ru. In addition, the use of silicates, molybdates, and phosphates led to the generation of a significant unoptimized soluble glass phase, which made Supercalcine susceptible to phase-specific dissolution in water. As a result, work on silicate-based ceramics has not been pursued.

Aluminate-based Ceramics

Aluminate-based ceramic waste forms were developed by Rockwell International under the name "tailored" ceramics. The phases present included corundum, spinel, magnetoplumbite, uraninite, nepheline, and a glass phase. The original formulation was made to incorporate the high-aluminum type of Savannah River high-level defense waste. When higher-iron waste streams were considered, it was not possible to form a satisfactory phase to incorporate Cs, Sr, and Ba, nor could a highly stable crystalline phase be formed to incorporate the alkali in the waste stream. This led to the development of a combined aluminate-titanate waste form known as RSC-S29. Its phases included zirconolite, magnetoplumbite, magnetite, spinel, murataite, and a small amount of glass phase.

The ceramic material produced by the NAC process contains nepheline and mullite fused to alumina particles ($\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$).

Phosphate-based Ceramics

Phosphate-based ceramic waste forms have been developed by Boatner, Sales, and co-workers at Oak Ridge and by researchers at Penn State. They have included monazite, sodium zirconium phosphate, sodium titanium phosphate, and berlinite (AlPO_4).

Sodium zirconium phosphate [$\text{NaZr}_2(\text{PO}_4)_3$] has been proposed as a single-phase ceramic waste form. It has been prepared by standard sol-gel and sintering techniques using loadings of 10 to 30 wt.% of PW-4b and 20 to 56 wt.% loading of mixed zirconia/alumina waste from the Idaho Chemical Processing Plant (ICPP).

Titanate-based Ceramics

Titanate-based ceramic waste forms have been developed by Sandia National Laboratories by Ringwood and co-workers in Australia and by Lawrence Livermore National Laboratory. They capitalize on the extremely high durability of titanate minerals and their ability to incorporate radionuclides of concern.

The SYNROC waste form, which is based on titanate phases found in gem gravels that have survived for hundreds of millions of years, has been well characterized and the database is, in general, as complete as for borosilicate glass. SYNROC is more stable at elevated temperatures in a hydrothermal environment than borosilicate glass. Therefore, deeper

disposal sites in the earth's crust can be considered. The better physical performance of SYNROC as compared to borosilicate helps to maintain the waste form's mechanical integrity. There is no flow rate dependence of the leach rate, and the solubility of the main matrix component, TiO_2 , is 3 to 4 orders of magnitude lower than that of SiO_2 . This has led to the development of another TiO_2 -based ceramic waste form.

Natural analogues are available for the evaluation of long-term radiation damage and leaching phenomena. A prototype pilot plant has been built for testing the production of non-radioactive SYNROC on a large scale. There is only one last step, "hot" operation, required to demonstrate and evaluate industrial application of the SYNROC fabrication process.

SYNROC-C was developed to incorporate high-level waste from the reprocessing of nuclear power reactor fuel. It is a fine-grained, polyphase crystalline ceramic composed primarily of the minerals hollandite, zirconolite, perovskite, and titanium oxides and/or minor calcium-aluminum titanates, plus small amounts of metallic alloys and a calcium-rich phosphate. The first three phases are intentionally chosen to incorporate radionuclides. The titanium oxides serve as a buffer to ensure that sufficient Ti is present. The metallic alloys incorporate the noble and reduced metals, and the phosphate incorporates the phosphorous present in Purex (Plutonium and Uranium Extraction) waste streams.

SYNROC-D was developed to incorporate Savannah River composite high-level defense waste and was selected as the alternative to borosilicate glass for this purpose. It is also a fine-grained polyphase ceramic. Its phases are zirconolite, perovskite, spinel, nepheline, and a silicate glass.

Glass-Ceramics

Glass-ceramic waste forms have been studied in Germany, the U.S., Japan, Sweden, the U.S.S.R., and Canada. In the U.S., the main efforts have been carried out at the Pacific Northwest Laboratory and the Idaho National Engineering Laboratory on waste forms known as basalt glass ceramics and iron-enriched basalt. The latter is a fusion-cast partly crystalline ceramic prepared from oxides of Si, Al, Fe, Ca, Mg, Ti, K, and Na, together with non-radioactive simulants or actual wastes. This waste form has been studied for use with TRU wastes and with defense high-level wastes from the Idaho Chemical Processing Plant and the Savannah River Site. The crystalline phases in this glass-ceramic material have included spinel, plagioclase, augite, fluorapatite, zircon, fluorite, cristobalite, and mullite. The glass is an aluminosilicate glass. The material is melted at 1,400-1,500°C (2,552-2,732°F), cast, and heat-treated at 1,000-1,100°C (1,832-2,012°F) to form the crystals. The Canadian glass ceramic work has focused on sphene-based material, which is composed of oxides of Na, Al, Ca, Ti, and Si, and nuclear wastes.

Chemically Bonded Ceramics

Chemically bonded ceramics are formed at temperatures near room temperature. The character of the bonding after heating to relatively low temperatures is dominated by ionic and covalent bonds, as compared with the weaker Van der Waals and hydrogen bonding that is dominant in hydraulic cements. Aside from variations of traditional hydraulic cement compositions, it appears that the most attention within this category of materials has been placed on phosphate-bonded ceramics. Phosphate cements are commercially available and have been applied to heavy-metal-containing wastes.

Organic Binders

Organic binders are being studied extensively in the U.S. and in Europe for immobilization of low-level wastes generated at nuclear power plants, research laboratories, and industrial production facilities. Many candidate organic binders are already produced commercially, while others remain in various developmental stages.

Organic binders are predominantly polymeric materials comprised of small, simple repeating units (monomers). They are synthesized by polymerization processes such as addition or condensation mechanisms, which yield high molecular weight macromolecules that consist of hundreds of monomer units. The degree and rate of polymerization can be controlled by varying the content of catalysts (initiators), accelerators, and inhibitors and by varying processing parameters such as temperature and pressure.

The macromolecular structure that results from polymerization processes can vary substantially. In some cases, polymerization results in linear repetition that gives rise to long polymer chains. In other cases, the chains are branched or cross-linked to form three-dimensional network structures. Either of these network structures provides encapsulation of the wastes and gives structural stability to the waste form. Crosslinking is known to result in a network structure with better chemical and mechanical properties than those of branched polymers.

Organic binders are categorized as thermoplastics or thermosetting polymers. Thermoplastics (linear or branched polymers) flow at elevated temperatures [~ 80 - 180°C (176 - 356°F)] and are easily molded. Thermoplastic materials and their associated technologies have been extensively studied and have been in use in various industries for over 50 years. Associated processes for solidification are relatively simple and are readily adaptable. On the other hand, thermosets have crosslinked polymer chains and set at room or elevated temperatures to form rigid solids that do not flow. For polymerization, thermosets require additional constituents such as catalysts and promoters.

Table 37 lists common thermoplastic and thermosetting binders that have been identified as candidates for final waste forms. Each of these candidate materials possesses a unique set of properties that may be suited for a given application. Only extensively studied thermoplastic (polyethylene and bitumen) and thermosetting (vinyl ester styrene, epoxy, and urea formaldehyde) binders possessing superior properties will be discussed.

TABLE 37
VARIOUS ORGANIC BINDERS FOR FINAL WASTE FORMS

THERMOPLASTIC SYSTEMS

Polyethylene
Bitumen
Polyvinyl chloride
Polymethyl methacrylate

THERMOSETTING SYSTEMS

Polyesters (vinyl ester styrene)
Epoxy
Urea formaldehyde (UF)
Polyurethanes

Source: *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

Organic binders contain the waste material by microencapsulation. The waste is surrounded, immobilized, and isolated from the environment by the highly impervious network structure of polymers. For thermoplastics, because there is no direct chemical interaction between the waste and the organic binder, various waste types can be successfully incorporated. This is especially advantageous for containment of complex mixed wastes. However, thermosets can be limited in their use because of the possibility of interference with polymerization by waste stream chemicals.

Thermoplastics and thermosets have excellent chemical tolerance and are compatible with various low-level waste streams (both aqueous and solid) such as boric acid concentrates, ion-exchange resins, alkaline waste solutions, and sludges. In general, organic binders incorporated with a variety of waste streams and loadings have exhibited excellent nuclide retention and leach performance properties. In particular, bitumen has been found to provide better retention characteristics for arsenic compared to some other binder systems.

Both thermoplastics and thermosets exhibit high waste-loading capacities. Waste loadings of 40-50 wt.% are common for organic binders, and waste loadings as high as 70 per cent have been achieved in some systems. For thermoplastics, there is a large volume reduction of aqueous wastes due to evaporation of contained water during elevated temperature processing. This results in a high waste volume efficiency for these binders. Moreover, because of the low processing temperatures, organic binders do not generate secondary waste streams with volatile metals.

Compressive strengths of organic binders (both thermoplastics and thermosets) are lower than those of glass and some cement waste forms and range between 13.8 and 55.2 MPa (2,000 and 8,000 psi) for a variety of waste types and loadings. Furthermore, thermosets have higher strengths than thermoplastics because of their crosslinked polymer chain structure. Thermoplastics lose their mechanical integrity on heating, but regain it on cooling.

ADVANTAGES/DISADVANTAGES OVERVIEW

The following sections summarize the advantages and disadvantages of the various waste form choices.

Glass

The advantages and disadvantages of using glass as a final waste form are listed in Table 38.

TABLE 38
ADVANTAGES AND DISADVANTAGES OF GLASS WASTE FORMS

ADVANTAGES

No free liquids
Chemical durability
Biological durability
Compositional flexibility
Leach resistance
Compressive strength
Physical durability

DISADVANTAGES

Off-gas system
Leach resistance
Limitations on organic materials in the feed
Limitations on metals in the feed
Solubility limits for certain elements
Disposal of spent vitrification units
Limited experience with LLMW form
Waste stream compatibility
Maintenance requirements

Source: *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

Hydraulic Cement

The advantages and disadvantages of using hydraulic cement as a final waste form are listed in Table 39.

TABLE 39
ADVANTAGES AND DISADVANTAGES OF HYDRAULIC CEMENT
WASTE FORMS

ADVANTAGES

Compressive strength
Thermal cycling degradation
Radiation stability
Biological degradation
Leach performance
Immersion stability
Free liquids
Chemical durability
RCRA compliance
Compositional flexibility
Processing and availability
Ability to solidify chemical salts and salt solutions

DISADVANTAGES

Unsuitable waste streams
Limited-use waste streams:
Porosity
Chemical instability
Sensitivity to chemical changes
Low leach resistance
Decrease in physical strength
Waste volume loadings
Water immersion degradation
Free liquid formation
RCRA compliance on organic liquid wastes
Heat of hydration
Large volume increase

Source: Adapted from *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

Sulfur Polymer Cement

The advantages and disadvantages of using sulfur polymer cement as a final waste form are listed in Table 40.

TABLE 40
ADVANTAGES AND DISADVANTAGES OF SULFUR POLYMER
CEMENT WASTE FORMS

ADVANTAGES

Immobilization of toxic metals
Remediation capability
Saving contaminated land
Compressive strength
Resistance to thermal cycling
Radiation stability
Biological stability
Leach resistance
Immersion stability
No free liquids
No gas generation
LDR compliance
Compositional flexibility
Operational advantages
Chemical durability and subsidence
resistance
Minimum secondary waste stream
Waste loading

DISADVANTAGES

Off-gas system
Disposal restrictions
Waste limitations
Flammability and explosivity
Preheating disposal containers and waste
Questionable biodegradation stability

Source: Adapted from *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

Ceramic

The advantages and disadvantages of using ceramic as a final waste form are listed in Table 41.

TABLE 41
ADVANTAGES AND DISADVANTAGES OF CERAMIC WASTE
FORMS

ADVANTAGES

Compressive strength
Resistance to thermal cycling
Radiation stability
Biological degradation

Leach performance
Immersion stability
No free liquids
Chemical durability
Gas generation
LDR compliance
Compositional flexibility
High waste loading
Minimization of secondary waste streams

DISADVANTAGES

Compositional flexibility
Particle size reduction
Radioactive powders
Off-gas system if volatile or semi-volatile
organics or nitrates are present

Source: *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

Organic Binders

The advantages and disadvantages of using organic binders as a final waste form are listed in Table 42.

TABLE 42
ADVANTAGES AND DISADVANTAGES OF ORGANIC BINDER
WASTE FORMS

ADVANTAGES

DISADVANTAGES

Thermoplastics

Solidification
Compatibility/versatility
Insensitive to waste chemistry changes
Water resistant
Low temperature processing
Waste volume efficiency
Leach resistance
Water immersion testing
Waste loading capacity
Resistance to thermal cycling
Biological stability

Physical stability
Pretreatment
Incompatible waste streams
Flammability
Leach resistance
Compressive strength
Radiation stability
Thermal stability

Thermosets

Compatibility/versatility
Leach resistance
Low temperature processing
Waste loading capacity
Resistance to thermal cycling
Biological stability

Waste stream properties must be monitored
Incompatible waste streams
Limited shelf life
Free liquids
Compressive strength
Radiation stability
Thermal stability

Source: *Technical Area Status Report for Low-Level Mixed Waste Final Forms*, prepared by J.L. Mayberry and L.M. DeWitt (SAIC) for U.S. DOE Mixed Waste Integrated Program, Office of Technology Development, DOE/MWIP-3, Aug. 1993.

CHAPTER 6. ECONOMIC ANALYSIS

The economic analysis presented in this chapter is KEI's adaptation and expansion of work that has been previously funded by the DOE. In particular, KEI based the performance scenario and the final waste outputs (both of which are described later in this chapter) on a mass balance provided by the NAC researchers. KEI also relied on assumptions made in a 1992 NAC cost estimate done by Martin Marietta cost estimator, David Brashears (Central Engineering Services). The costs for vitrification and grouting were extrapolated from cost data that is presented in the report, *Waste Management Facilities Cost Information (WMFCI) for Mixed Low-Level Waste* (EGG-WM-10962, March 1994).

The WMFCI task was performed by a project team from EG&G Idaho, Inc. and the Environmental Services Division of the Morrison Knudsen (MK) Corp. EG&G and MK were selected for this task because of their combined expertise in design, construction, and operation of TSD facilities for DOE sites and for the nuclear industry. Please note that KEI refers to the LLW document produced by this team by the following abbreviations, which are used interchangeably, WMFCI and EG&G.

GENERAL ASSUMPTIONS AND METHODOLOGY

The general assumptions presented here are based on information from the WMFCI document referenced above. The WMFCI document provides cost information for alternatives involving waste management treatment, storage, and disposal (TSD) facilities needed for managing alpha and non-alpha mixed low-level waste (MLLW). Alpha MLLW contains transuranic nuclides at concentrations ranging from 10-100 nCi/g.

KEI based much of the economic analysis that is presented in this chapter on the cost data and the methodology used by the WMFCI team. However, because the maximum throughput capacities of the EG&G models were much less than that of the performance scenario chosen by KEI, it was necessary to extrapolate the data. The assumptions and methodology made by the WMFCI team and by KEI for making these extrapolations are discussed in the sections to follow.

KEI developed a computer model based on the data presented in the WMFCI document in order to easily compare costs that result from different assumptions and to easily expand on this work in future projects. This model calculates the costs for vitrification and grouting at throughputs beyond the upper bounds of the WMFCI charts, which are 455 kg/hr for vitrification and 1,818 kg/hr for grouting. Appendix Tables 3-3 to 3-8 present the upper-bound data for grouting and 3-11 to 3-17 for vitrification. The KEI model was used to determine main component vitrification and grouting costs at 7,000 kg/hr. The subcomponent costs were obtained using the per cents obtained for the upper-bound case. Appendix Table 3-9, 3-10, and 3-18 present the extrapolated 7,000 kg/hr data.

FACILITY CONSTRUCTION AND OWNERSHIP

The WMFCI report assumed that all facility equipment will be new and placed within either totally new structures or modified existing structures. Modified structures will be upgraded to house equipment required for processing alpha and non-alpha waste. The upgrades will include construction of interior walls, roof modifications, secondary containment, and other improvements that are necessary to meet all technical and regulatory standards applicable to each treatment facility. Site development costs such as utilities and road work are

included within 100 feet of the facility only. Site infrastructure costs are not included. All facilities were assumed by the WMFCI team to be government owned and contractor operated. As a result, KEI assumed that the cost of land was not included in the cost model.

THROUGHPUT

The WMFCI reports that, for small generator facilities, data from the DOE *Mixed Waste Inventory Report* indicate that the capacity needs of representative small generator DOE R&D laboratory installations typically range from 176-704 ft³/yr (5 to 20 m³/yr). This capacity, which ranges from 25 to 100 drums (55-gallon) per year, is much less than the smallest throughput offered by most commercially available processing equipment. Therefore, the equipment included for small generator waste treatment could have the potential to process larger capacities than are actually needed. For grout stabilization, the capacity range of the costing module is 9.1 kg/hr (alpha, non-alpha, and portable) for small generators and 181.4-1814.3 kg/hr (alpha and non-alpha) for large generators. For vitrification, the capacity range of the costing module is 18.1-453.6 kg/hr (alpha) and 22.7-453.6 (non-alpha) for large generators.

MODULAR FACILITY

The planning level life-cycle cost estimates in the WMFCI reports are based on a set of facility modules, each of which may be used alone or combined.

TECHNOLOGY AVAILABLE

Cost information in the WMFCI report is based on available technologies. The basic rule employed in using the technologies is that at least one vendor must commercially offer the given technology without incurring upfront basic R&D costs.

ESCALATION RATES

The WMFCI Planning Life-cycle Cost (PLCC) Estimates are developed based on 1994 dollars. The time value of money or escalation for expenditures occurring at different time frames has not been considered in the estimates. The WMFCI costs have been summarized by major program elements (pre-operation, construction, O&M, and D&D) so that the user could apply appropriate escalation rates to represent the specific schedule requirements. KEI obtained additional data from the authors of the report in order to give a more detailed accounting of the cost factors.

FACILITY OPERATION

For large generator facilities, the PLCC estimates are based on the assumption that the operating period of the facility is 10 years. New facilities would have a total operational life of 30 years. During this period, the facility may operate a maximum of 24 hours/day, 240 days/year, and at 70 per cent availability during operation. This is equivalent to 168 days/year or 4,032 hours/year of operation.

KEI adjusted the basis to an operating period of 20 years with 5,256 hour/year (365 days per year, 24 hours per day, with 60 per cent availability) in order to make a comparison with the existing NAC cost estimate.

To compensate for the over-capacity of the small generator alpha and non-alpha waste treatment modules, the WMFCI report assumed that the operations will be done on a batch basis. It is also assumed that alpha-contaminated wastes are handled only at large generator facilities.

COST ASSESSMENT

Equipment costs were compared to the extent possible by the WMFCI team with data from anchor facilities to establish a cost confidence level within the boundaries established for the PLCC estimates. Both the DOE and the commercial nuclear industry are now planning or operating similar facilities. These facilities were surveyed by the WMFCI team to obtain capacity, cost data, and other information needed to support the WMFCI data. Before using these costs, the data were adjusted to account for capacity differences and escalation.

Additional assessment activities by the team included a review of existing DOE facility capital and operating costs for comparison. Existing DOE facilities that have been evaluated include: Waste Experimental Reduction Facility (incineration, shredding, and compaction) at the INEL, the Controlled Air Incinerator at Los Alamos National Laboratory (LANL), the Toxic Substances Control Act Incinerator at ORNL, the Supercompactor and Repackaging Facility (SARF) at Rocky Flats, Radioactive Waste Management Complex Low-Level Waste Disposal at the INEL, and the Transportable Waste Water Treatment Unit from the Uranium Mill Tailings Remedial Action Project (UMTRA). Planned DOE facility costs at the INEL were also evaluated for the Radioactive Waste Storage Facility, the Waste Characterization Facility, the Idaho Waste Processing Facility, and the Mixed Low-Level Waste Treatment Facility. Other facilities evaluated include: the Illinois Compact Low-Level Waste Engineered Disposal Facility, and the Commonwealth of Massachusetts Low-Level Radioactive Waste Disposal.

Estimates for new facility construction are based on the conditions for the INEL site including utility, labor and the related design, construction, operation, and management factors. The INEL costs are considered to represent the mid-range costs within the DOE complex. Site specific evaluations should be performed to improve the cost estimating accuracy.

COST BASIS

Whenever possible, the WMFCI team selected baseline capacities to be the same as those of an existing facility or one estimated earlier in the task. This approach, referred to as anchoring (see definitions for "Anchor Facility" and "Anchoring" in Appendix 2), provided a reference point that could be used as the basis for estimating the various cost components. Furthermore, anchoring provides a comparison of the estimates in this report with either the actual costs incurred by an operating facility or estimates of facilities that are in an advanced state of design and construction. Data from the study were based on "bottoms-up" cost estimates of three different facility sizes: small, medium, and large. Whenever possible, the baseline capacities were selected to be the same as an existing facility.

Using the given capacities, a preconceptual design package for each facility was developed and used as the basis for the PLCC estimates. After unit operations were defined, major

equipment lists and building configurations were developed for each of these operations. The design packages used as much data from existing or planned commercial and DOE anchor facilities as possible. New designs were generated only when existing data were not available.

The PLCC estimate for each facility was divided into four cost elements. The total facility PLCC estimates were obtained by taking the sum of the relevant cost estimates. Existing facilities costs only require the O&M and D&D costs. New facilities include all pre-operation costs, facility construction equipment, O&M, and D&D. The O&M costs can be factored from the cost curves to obtain operating costs for periods other than 10 years. [KEI's analysis used an operating period of 20 years.] Total WMFCI life-cycle costs include pre-operation costs, facility construction equipment, O&M, and D&D for an operation and maintenance period of ten years. KEI's life-cycle costs include transportation, disposal, and additional off-gas treatment as well.

For large generator facilities, unique parametric cost equations were developed by the WMFCI team for the pre-operations, facility construction, operations and maintenance, and decommissioning and decontamination cost elements. These equations were developed based on the baseline bottoms-up estimates regressed over a range of facility capacities for each cost module. There are equations that describe MLLW/LLW costs, alpha MLLW/LLW costs, MLLW Full-Time Equivalents (FTEs), and alpha MLLW FTEs. KEI relied on the cost data rather than FTE data.

Linear and non-linear approaches were used by the WMFCI team to provide the best fit cost curves. The curves were developed to represent the full range of facility costs over the estimated capacity.

Pre-operations

The pre-operations costs include studies, bench-scale tests, and demonstration, which are relatively small and were obtained by the WMFCI team by estimating research manpower and equipment needs. The major portion of the pre-operations costs are operations-budget funded activities, which include conceptual design, safety assurance, National Environmental Policy Act of 1969 (NEPA), compliance efforts, permitting, preparation for operation, and project management costs. All other subcomponents of the cost of operations-budget funded activities were estimated as a percentage of the construction cost. Note that NEPA costs of \$6 million are included in only the Receiving and Inspection Module for the large facility cost estimates. The NEPA and safety assurance costs for the small generator are included in only the front-end and back-end support module. Additionally, the MLLW and LLW module costs have been defined as equivalent. Although differences in handling regulations and permitting may create small differences in the cost estimates.

Facility Construction

Facility construction costs consist of two key subcomponents: major equipment costs and building costs. This cost element requires capital equipment and line item funding.

Cost estimates for major equipment were obtained by the WMFCI team either from a similar facility, from an anchor facility, by soliciting budgetary costs from the suppliers, or by making engineering judgments. KEI based costs of the major NAC/NAG/NAX equipment

components on the 1992 MMES cost estimate. For vitrification and grouting, the costs were extrapolated from the WMFCI data.

The WMFCI building costs were estimated either by multiplying building unit costs by the square footage allocated to each unit operation in the layouts, or by developing building material and labor requirements and multiplying them by the appropriate unit rates. Building costs for modifications to existing structures were estimated by developing material and labor requirements for building cost components. It is assumed that modifying an existing facility will not require site preparation and superstructure construction necessary for a new facility. All other building cost components will be identical to that of a new facility. Personal conversations with a member of the WMFCI team (Belenda Wong) revealed the building cost assumptions presented in Table 43.

TABLE 43
EG&G BUILDING COST ASSUMPTIONS

Building Segment	Non-alpha, \$/ft²	Alpha, \$/ft²
Administrative areas	180	180
Medium hazard areas	420	420
Maintenance areas	800	1200
Alpha processing areas	---	1500

Source: Belenda Wong, Morrison Knudson Corp.

Once the equipment and building costs were estimated by the WMFCI team for each facility, they were totaled and multiplied by a factor to allow for the construction contractor's indirect costs. The sum of the equipment, building, and indirect costs were then multiplied by applicable factors to allow for design, inspection, construction management, and project management costs. Allowances were also included for management reserve and contingencies.

Operations and Maintenance

Operations and maintenance (O&M) consists of five subcomponents: operating labor, utilities, consumable material, and maintenance (parts, equipment, and labor). The first three subcomponents were estimated by analyzing the requirements of each facility at the unit-operations level. The maintenance costs were estimated as a percentage of the original equipment installed at the facility. Allowances were also included for management reserve and contingencies.

Decontamination and Decommissioning

Decontamination and decommissioning (D&D) at facility closure was estimated by multiplying a D&D unit rate of \$450 by the facility square footage.

Waste Disposal

KEI based its analysis of on-site waste disposal costs on the WMFCI data. KEI estimated costs for two different means of disposal: engineered disposal and shallow-land disposal. Note that total disposal costs are comprised of two components: front-end support plus disposal cost.

Front-end Support

The disposal front-end support module unit operations include truck loading and unloading areas, administrative offices, analytical laboratory facilities, and truck inspection and washdown. The vehicles are not included in the module.

The containers arrive in a transport vehicle, are unloaded using a forklift or overhead bridge crane, and are placed in a staging area. The containers are visually examined, labeled, logged, and sent to inspection and assay. At the inspection and assay unit, the category of the received waste is verified against the results obtained from the back-end treatment or storage modules. After inspection, the drums are sent to disposal.

The cost and design of this module are based on several simplifying assumptions and information gathered from a variety of sources. Major equipment and module cost items for this module are based on data obtained from the Illinois LLW Disposal Facility (Morrison Knudsen/Chem Nuclear Services 1991). Staffing levels were estimated based on the number of personnel required for support of approximately ten separate support functions. FTE staffing levels are based on data obtained from the Illinois LLW Disposal Facility (Morrison Knudsen/Chem Nuclear Services 1991). A \$1 million allowance is made for the analytical instruments and components needed for a mixed-waste laboratory.

Engineered Disposal

The engineered disposal module consists of engineered disposal units that are based on the Illinois LLW disposal module design, shown in Figures 3a and 3b, which uses an earth mound and concrete cell concept (Morrison Knudsen/Chem Nuclear Services 1991). Engineered disposal modules for non-RCRA waste and RCRA waste are essentially the same except that a RCRA disposal unit has a double leachate collection system in compliance with the RCRA requirements.

The unit operations include receiving the inspected drums, placing the drums into concrete canisters, and constructing the disposal units that will house incoming concrete waste canisters. Disposal unit construction includes foundation, leachate collection system, and monitoring system, concrete vaults, and earth covers. Construction of the modules is intended to be a continuous process concurrent with the placement of the canisters.

O&M consumables, including empty concrete canisters, grout, sand, and personal protective equipment, must be purchased.

Function and Operation

Upon receipt of the containers, they are packaged into concrete canisters that are then sealed with grout. The canisters are transported to the disposal units for placement. Each disposal unit is comprised of a double row of concrete cells with an access aisle between the

rows. Concrete canisters that arrive from the packaging area are placed in a cell by overhead crane or forklift from the access aisle and stacked three canisters high. Once the cell is full, it is backfilled with sand and a concrete cover is concurrently constructed to seal the cells.

The cells are capped with an earth layer that is engineered to withstand long-term environmental and weathering effects. The layered cap consists of sandy drain layers placed directly over the cells, an impervious clay layer, a high-density polyethylene liner, and another drain layer to deter seepage into the cells. The top layer consists of either subsoil and vegetative material or subsoil, bedding, and riprap. The monitoring system includes sensors that will detect any leakage from the cells.

D&D includes module demolition and the disposal unit maintenance. Disposal unit maintenance is planned in two stages, each with two substages: (1) short-term maintenance, which consists of closure and post-closure periods, and (2) long-term maintenance, which consists of active institutional care and passive institutional care.

Closure activities take place during the first two years after the facility ceases to accept waste. Closure includes decontamination of the modules, initial demolition of buildings, site development, closure of the cells, site remediation, and monitoring of the cell performance and ground water. Years one through ten after the facility ceases to accept waste are designated as the post-closure period. During this period, monitoring of the ground water and cell performance will continue, as well as site remediation and restoration. Active institutional care is planned for 11 to 100 years following the post-closure period. During this stage, any buildings not previously demolished are torn down and all site services are removed, in addition to on-going monitoring activities. The last stage, passive institutional care, extends from 101 to 300 years after the facility ceases to accept waste. Passive institutional care includes closing the center aisles of the vaults, completing the earth caps and site grading, removing the retention ponds and retaining walls, and installing passive drains. Site maintenance is discontinued after 300 years.

Cost Basis, Assumptions, and Results

Major equipment capital cost items are a forklift and an overhead crane for placement of the drums into canisters and placement of filled canisters into the concrete cells. Costs for these items are based on vendor quotes. Estimated FTE staffing is based on data on the Illinois LLW Disposal Facility (Morrison Knudsen/Chem Nuclear Services 1991) and a DOE conceptual design report (DOE 1987).

Construction of the disposal units is a major cost item. A preconceptual design of one disposal unit that applies to all modules, including the concrete cell and cover design, was developed based on the design of the Illinois LLW Disposal Facility. A unit cost per cell was developed based on data from the Illinois facility, and an estimate was generated according to the rate of incoming waste and number of cells required for each small, medium, and large module. Minimum size capacity is provided as a lower bound for the smallest economical engineering designed facility. Estimates are based on a disposal facility in accordance with DOE and NRC criteria, but an NRC license is not assumed.

Figure 3A Equipment layout for engineered disposal module (module AGDSP).

Figure 3B Process functional diagram for engineered disposal module (module AGDSP).

Shallow-land Disposal

Shallow-land disposal essentially consists of trench disposal without engineered features. The cost for a shallow-land disposal consists of three components: front-end capital cost, disposal O&M cost, and site closure cost. Since shallow-land trench disposal units are commonly used by both the DOE and the commercial nuclear industry, a preconceptual design of disposal units to develop capital and O&M costs was not necessary.

Containers received from the disposal front-end support module are transported to a disposal unit. Each disposal unit consists of an excavated trench. The containers are stacked in the bottom of the trench using a boom crane. After one row is completed, a layer of fill is placed on top of the containers. The cap consists of at least seven feet of engineered fill dirt and clay. The disposal site includes all of the appropriate storm drainage collection and discharge equipment. Site monitoring includes both ground water and air sampling systems. O&M consumables, including personal protective equipment, must be purchased.

KEI'S Analysis

KEI's cost analysis can be broken down into two segments: 1) grouting and vitrification and 2) NAC/NAG/NAX. The analyses of the grouting and vitrification facility costs are based on extrapolations of WMFCI data. However, because the NAC/NAG/NAX process was not addressed by the WMFCI team, KEI had to develop another method to determine the costs. Nevertheless, KEI made every attempt to make the cost components used in the NAC/NAG/NAX analysis consistent with those used in the vitrification and grouting analyses so that direct comparisons of the numbers are relevant.

Grouting and Vitrification

According to the WMFCI report, costs should not be extrapolated for facility capacities outside the defined range of capacities. However, the capacity assumed by KEI for the Hanford-scale grouting and vitrification facilities were outside of the range. Personal communication with Mike Sherick (EG&G Technical Support) indicated that it is acceptable to use the Six-Tenths Rule to make estimates outside of the range up to four times the high end of the mass flow range. Based on this rule-of-thumb, grouting fell into the Six-Tenths Rule range, but vitrification did not.

Because of this, it was necessary to find a better way to extrapolate the data for vitrification. KEI obtained the congressional budget for the Savannah River HLW vitrification facility and used 80 per cent of the estimated life-cycle cost for the 7.5 ton (6,800 kg) of glass per day facility as the "anchor" in the alpha extrapolation. From the Congressional Budget presented in Appendix Table 4-7, KEI estimated the HLW life-cycle cost to be \$6.59 billion, excluding waste transportation and disposal costs. KEI assumed that the LLW life-cycle cost is 80 per cent of this or \$5.27 billion. Table 44 summarizes the numbers that comprise this estimate.

TABLE 44
VITRIFICATION ANCHOR DATA POINTS FOR X/10THS
EXTRAPOLATION

COST COMPONENT	SAVANNAH RIVER HLW COSTS*	SAVANNAH RIVER ALPHA COSTS**
Facility construction	1.29 x10 ⁹	1.03 x10 ⁹
Pre-operations	1.18 x10 ⁹	9.44 x10 ⁸
Operations & maintenance	4.00 x10 ⁹	3.2 x10 ⁹
Decommissioning & decontamination	1.16 x10 ⁸	9.28x10 ⁷
TOTAL	6.59 x10⁹	5.27 x10⁹

* Congressional budget figures.

** Assumed to be 80 per cent of HLW costs.

Source: KEI

The HLW estimate is comprised of facility construction (\$2.47x10⁹ - \$1.18x10⁹), pre-operations (\$1.18x10⁹), O&M (\$200 million per year for 20 years), and D&D (9% of facility construction). Again note that the numbers in parentheses were obtained from the Congressional Budget figure presented in Appendix 4.

The four data points were added to the power curves in the alpha vitrification module (10-100 nCi/g TRU). With this expanded curve, the "X-Tenths Rule" was applied in order to determine the actual factors that resulted for the anchored curve. These factors were used to extrapolate the non-alpha curves to the higher capacity. Table 45 summarizes the X/10ths factors that were calculated.

TABLE 45
VITRIFICATION X/10THS FACTORS

COST COMPONENT	X/10ths VALUE
Facility construction	0.6356
Operation & maintenance	0.8740
Pre-operations	1.2925
Decommissioning & decontamination	0.6564
OVERALL	0.8646

Source: KEI

The WMFCI curves only provide a way to extrapolate the overall costs for the major four categories. Each category is, however, comprised of many subcategories. In order to fill in the gaps, KEI used an "anchor" case (i.e., 1,818 kg/hr input capacity for grouting and 455 kg/hr for vitrification) where all the cost data are known. KEI put each subcomponent cost

in terms of per cent of its main component cost. Detailed cost data for the subcategories can be found in Appendix Tables 3-11 to 3-18.

Nitrate to Ammonia and Ceramic and Glass (NAC/NAG/NAX)

KEI's estimate for the NAC process is based on the capital equipment and O&M costs from the 1992 MMES estimate. Although it was necessary to adjust the 1992 costs in many instances, particularly for the alpha case, they provided the framework for KEI's analysis, which includes the same cost components as those in the EG&G analysis.

KEI determined installation costs for the NAC/NAG/NAX equipment by analyzing the relationship of installed equipment cost for the known EG&G vitrification facility (455 kg/hr) and using appropriate percentages to determine the installation costs for the NAC/NAG/NAX equipment. In order to include the EG&G cost components that the 1992 estimate did not, KEI assumed grout figures for a low estimate and an average of grout and vitrification for a high estimate. For the O&M costs for the NAG vitrification unit, KEI assumed half of that for vitrification. The NAG O&M cost should be lower because the quantity of material being fed to that unit should be significantly less than for vitrification. The low D&D estimate for NAC/NAG/NAX is based on the estimated square footage while the high estimate is an average of grouting and vitrification.

PERFORMANCE SCENARIO

KEI's cost analysis is based on the following performance scenario, which describes the assumed LLW waste feed that was used in determining the costs of NAC/NAG/NAX, vitrification, and grouting. This section also describes the assumed final waste forms from these processes.

WASTE FEED

Table 46 shows the composition of the Hanford simulant that was used in an ORNL mass balance for the NAC/NAG/NAX process. The ORNL researchers assumed a feed rate of 1 L/min or 76.748 kg/hr of simulated Hanford saltcake solution (1.28 g/cm³, 4.3 M Na). KEI's cost estimate for the NAC/NAG/NAX process, which was based on the flow sheet and mass balance presented in Figure 4 and Table 47, assumes a feed rate of 1,084 kg/hr NO₃ (92 L/min or 7,061 kg/hr of feed). Note that the 1,200 kg/hr assumed in the 1992 cost estimate (see Appendix 4) was not used by KEI because it contains an error.

Although KEI's assumed feed throughput of 7,061 kg/hr is higher than the proposed Hanford scenario of 100-200 tons of glass (loaded with 25% of calcined feed solids) per day, KEI used this capacity to make a direct comparison of KEI's vitrification and grouting cost estimates with the existing NAC cost estimate.

Assumptions used in the following discussion are based on personal communications with Joe Carter of Savannah River, Frank Wooley of Corning Glass, and Merek Brandys of Catholic University. The calcining process decreases the mass of feed solids by approximately 30 per cent due to conversion to metal oxides. From Table 13, the composition of the Hanford feed contains 376 g/L of contaminants. Based on this, the entire 600 million liters of waste contains 2.25×10^8 kg of contaminants. Note, however, the actual

Hanford feed contains traces of many other contaminants besides the major ones, which are listed in Table 13.

Assuming a 20-year processing period, the annual quantity of solids to be processed is 1.13×10^7 kg/yr (2.25×10^8 kg/20 years). Assuming a 30 per cent reduction in mass after calcining, this quantity decreases to 7.91×10^6 kg/yr. Assuming 5,256 hr/yr, the feed rate of calcined solids is 1,505 kg/hr. The volume of liquid feed needed for this feed rate is determined by the following relationship, 2.25×10^8 kg/600 mil L = 1,505 kg/hr/x, where x is 4,013 L/hr or 5,137 kg/hr (1.28 kg/L). This compares with KEI's assumed hourly feed rate of 7,061 kg/hr. Note that the 4,013 L/hr does not include the liquid added as a result of pretreatments, which may bring the required throughput volume (assuming a 20-year period) closer to KEI's assumption. Based on information obtained from Joe Carter, Savannah River pretreatments add 35 per cent to the actual mass flow rate of the feed.

TABLE 46
FEED RATES FOR HANFORD SALTCAKE SIMULANT

CONTAMINANTS	ORNL SCALE*		HANFORD SCALE**	
	(1 L/MIN FEED)		(92 L/MIN FEED)	
	KG/HR	KG/YR	KG/HR	KG/YR
H ₂ O	56.473	296,822	5,196	27E+6
NaNO ₃	15.245	80,128	1,403	7.4E+6
Na, 27%	4.12			
NO ₃ , 73%	11.13			
NaNO ₂	0.975	5,1258	89.7	4.7E+5
Na, 33.3%	0.325			
NO ₂ , 66.7%	0.650			
Na ₂ SO ₄	0.485	2,549	44.6	2.3E+5
Na, 32.4%	0.157			
Na ₂ CO ₃	0.871	4,578	80.1	4.2E+5
Na, 43.4%	0.378			
Na ₃ PO ₄	0.871	4,578	80.1	4.2E+5
Na, 42.1%	0.367			
NaAlO ₂	0.934	4,909	85.9	4.5E+5
Na, 28.0%	0.262			
NaOH	0.894	4,699	82.2	4.3E+5
Na, 57.5%	0.514			
TOTAL	76.748	403,387	7,061	37E+6
Na, 8.0% (4.3 M)	6.123	32,182	563	3.0E+6
NO ₃ +NO ₂ , 15.3%	11.78	61,916	1,084	5.7E+6

* This feed (obtained from ORNL DWG 93A-856, 1.28 g/cm³) is 5 times the values from the ORNL material balance. Silica (24.02 kg/hr ORNL, 2,210 kg/hr Hanford) and aluminum (15.035 kg/hr ORNL, 1,383 kg/hr Hanford) are also fed to the reactor. This is a feed total of 115.79 kg/hr ORNL and 10,654 Hanford, excluding the nitrogen purge (15 kg/hr, 200 L/min, ORNL; 1,380 kg/hr Hanford).

** In order to make the feed match that used for the 1992 NAC cost estimate, it is necessary to multiply the ORNL-scale feed by 92 (460 times the values from the material balance). Basis: 20-year processing period, around-the-clock operations 365 days/year with 60% availability or 5,256 hr/yr.

Source: KEI

Fig. 4 Material Balance Flowsheet for the NAC Pilot Plant

ORNL DWG 93A-856

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TABLE 47
NAC/NAG/NAX MASS BALANCE SUMMARY

STREAM	COMPONENT	ORNL-SCALE, KG/HR	HANFORD- SCALE, KG/HR
Feed	NaNO ₃	15.245	1402.5
	NaNO ₂	0.975	89.7
	Na ₂ SO ₄	0.485	44.6
	Na ₂ CO ₃	0.871	80.1
	Na ₃ PO ₄	0.871	80.1
	NaAlO ₂	0.934	85.9
	NaOH	0.894	82.2
	H ₂ O	56.743	5220.4
	Subtotal	77.018	7085.5
Reaction Product <i>Pre Centrifuge</i> (1.56 g/cm ³)	Al	15.035	1383.2
	SiO ₂	24.01	2208.9
	Al(OH) ₃	28.372	2610.2
	NaAlO ₂ ·2.5H ₂ O	37.178	3420.4
	H ₂ O	88.654	8156.2
	SiO ₂	24.01	2208.9
	NaOH	2.65	243.8
	Other Na salts	6.57	604.4
	NaNO	0.090	8.28
	Subtotal	187.524	17252.2
<i>Post Centrifuge</i>	Al(OH) ₃	28.372	2610.2
	NaAlO ₂ ·2.5H ₂ O	26.022	2394.0
	H ₂ O	29.854	2746.6
	SiO ₂	24.01	2208.9
	NaOH	0.89	81.9
	Other Na salts	2.227	204.9
	NaNO	0.030	2.76
	Subtotal	111.405	10249.3
<i>Post Calcining</i> (2.6 g/cm ³)	Al(OH) ₃	28.372	2610.2
	NaAlO ₂	16.78	1544.8
	SiO ₂	24.01	2208.9
	NaOH	0.89	81.9
	Other Na salts	2.227	204.9
	NaNO	0.030	2.76
	Subtotal	72.3	6653.5

TABLE 47 (CONT.)
NAC/NAG/NAX MASS BALANCE SUMMARY

STREAM	COMPONENT	ORNL-SCALE, KG/HR	HANFORD- SCALE, KG/HR
Off-gas	NH ₃	3.295 (72.24 L/m)	303.1
	H ₂	0.153 (28.37 L/m)	14.1
	H ₂ O	0.96 (19.93 L/m)	88.3
	N ₂	15.0 (200 L/m)	1380.0
	Subtotal	19.4	1785.5

* Assumption: 5256 hr/yr

Source: Based on ORNL data

FINAL WASTE

Nitrate to Ammonia and Ceramic or Glass (NAC/NAG/NAX)

Table 48 shows the composition of the final waste forms from the NAC/NAG processes. KEI assumed the density of the final-waste form (both the glass and the ceramic) to be around 2.6 g/cm³ (163 lb/ft³). The determination of the final waste composition is based on Figure 4.

TABLE 48
COMPOSITION OF NAC/NAG FINAL WASTE PRODUCTS

COMPONENT	ORNL-PILOT-PLANT SCALE (1 LITER/MIN), KG/HR *	FULL-SCALE HANFORD PLANT (92 LITER/MIN), KG/HR **
CERAMIC		
Al(OH) ₃	28.372	2,610.22
NaAlO ₂	16.78	1,543.76
SiO ₂ (1.5 moles per mole Na)	24.01	2,208.92
Other Na salts	2.227	204.88
NaOH	0.89	81.88
NaNO	0.030	2.76
TOTAL	72.313	6,652.42
GLASS		
Al(OH) ₃	28.372	2,610.22
NaAlO ₂	16.78	1,543.76
SiO ₂ (1.5 moles per mole Na in feed)	24.01	2,208.92
Potential additional SiO ₂	Unknown	Unknown
Other Na salts	2.227	204.88
NaOH	0.89	81.88
NaNO	0.030	2.76
Fluxing agent	Unknown**	Unknown
TOTAL	72.313 + additional silica + fluxing agent	6,652.42 + additional silica + fluxing agent
GLASS-CERAMIC		
Al(OH) ₃	28.372	2,610.22
NaAlO ₂	16.78	1,543.76
SiO ₂ (1.5 moles per mole Na)	24.01	2,208.92
Other Na salts	2.227	204.88
NaOH	0.89	81.88
NaNO	0.030	2.76
TOTAL	72.313	6,652.42

* Amount of additional silica required the subject of future research.

** Experiments using B₂O₃ resulted in lowered viscosities, but some phase separations occurred.

Source: KEI

The following calculations, which are based on Figure 4, show the quantity of final waste that must be disposed in a pilot- and full-scale process:

NAC: Assuming calcining and sintering is a one-step process that produces marble- to pea-size clinker (1.95 g/cm³ bulk density):

Calculation of quantity of water in NaAlO₂•2.5H₂O:

$$\text{Molecular weight of NaAlO}_2 \cdot 2.5\text{H}_2\text{O} = 81.97 + (2.5 \times 18) = 127 \text{ g/mole}$$

$$1 \text{ mole of NaAlO}_2 \cdot 2.5\text{H}_2\text{O} = 64.5\% \text{ NaAlO}_2 + 35.5\% \text{ H}_2\text{O}$$

$$26.022 \text{ kg/hr of NaAlO}_2 \cdot 2.5\text{H}_2\text{O} = (0.645 \times 26.022)_{\text{NaAlO}_2} + (0.355 \times 26.022)_{\text{H}_2\text{O}} \\ = 16.784 \text{ kg/hr NaAlO}_2 + 9.238 \text{ kg/hr H}_2\text{O}$$

$$\text{Pilot-scale waste output} = \text{kg/hr (product slurry)} - \text{kg/hr (H}_2\text{O)} - \text{kg/hr (H}_2\text{O from NaAlO}_2 \cdot 2.5\text{H}_2\text{O)} \\ = 111.405 - 29.854 - 9.238 = 72.313 \text{ kg/hr}$$

$$\text{Full-scale waste output} = 92 \times [\text{pilot-scale waste}] \\ = 92 \times 72.313 = 6,653 \text{ kg/hr}$$

$$\text{Final waste volume} = 6,653 \text{ kg/hr} \times 1000 \text{ cm}^3 / 1.95 \text{ kg} \times \text{in}^3 / 16.39 \text{ cm}^3 \times \text{ft}^3 / 12^3 \text{ in}^3 \\ = 120.46 \text{ ft}^3/\text{hr} \times 5,256 \text{ hr/yr} = 633,163 \text{ ft}^3/\text{yr} \\ = 3.41 \text{ m}^3/\text{hr} \times 5,256 \text{ hr/yr} = 17,932 \text{ m}^3/\text{yr} \\ = 358,648 \text{ m}^3/20 \text{ yr} = 12,663,260 \text{ ft}^3/20 \text{ yr}$$

NAG: Assuming the reaction product (straight out of the reactor) is vitrified (2.6 g/cm³):

Because the water is driven off in the vitrifier as it was in the calciner, the waste output is that of NAC (6,653 kg/hr) plus 3 times (Terry Tiegs, ORNL Metals & Ceramics Div.) as much silica as was used for NAC (6,627 kg/hr silica: 3 x 2,209 kg/hr silica, i.e., 4.5 moles silica:1 mole sodium) or 13,280 kg/hr.

$$\text{Full-scale waste volume} = 13,280 \text{ kg/hr} \times 1000 \text{ cm}^3 / 2.6 \text{ kg} \times \text{in}^3 / 16.39 \text{ cm}^3 \times \text{ft}^3 / 12^3 \text{ in}^3 \\ = 180.34 \text{ ft}^3/\text{hr} \times 5,256 \text{ hr/yr} = 947,889 \text{ ft}^3/\text{yr} \\ = 5.11 \text{ m}^3/\text{hr} \times 5,256 \text{ hr/yr} = 26,846 \text{ m}^3/\text{yr} \\ = 536,921 \text{ m}^3/20 \text{ yr} = 18,957,780 \text{ ft}^3/20 \text{ yr}$$

NAX: Assuming the calcined material is grouted:

Full-scale ungrouted waste volume

$$= 92 \times [\text{pilot-scale waste}] \\ = 92 \times 72.313 = 6,653 \text{ kg/hr} \\ = 6,653 \text{ kg/hr} \times 1000 \text{ cm}^3 / 1.3 \text{ kg} \times \text{in}^3 / 16.39 \text{ cm}^3 \times \text{ft}^3 / 12^3 \text{ in}^3 \\ = 180.68 \text{ ft}^3/\text{hr} \times 5,256 \text{ hr/yr} = 949,654 \text{ ft}^3/\text{yr}$$

$$\text{Grouted waste volume} = 180.68 \times 1.4 = 253.0 \text{ ft}^3/\text{hr}; 1,329,516 \text{ ft}^3/\text{yr} \\ = 5.12 \text{ m}^3/\text{hr} \times 1.4 = 7.17 \text{ m}^3/\text{hr}; 37,675 \text{ m}^3/\text{yr} \\ = 753,500 \text{ m}^3/20 \text{ yr} = 26,590,320 \text{ ft}^3/20 \text{ yr}$$

Grouting

Assuming there are 600 million liters of Hanford waste to be treated as LLW and that there is a 40 per cent increase in volume due to the grouting process, the quantity to be disposed is 840 million liters (29.7 million ft³; 840,000 m³). Assuming a 20-year processing period and 5,256 hr/yr, this results in a rate of 8 m³/hr. Based on one analysis (discussed later in this chapter), disposal of this volume of grouted material requires 158 vaults. According to Joe Carter of Savannah River, the SRP grouting facility (non-alpha) cost \$70 million seven or eight years ago.

The volume increase assumption was verified through a personal communication with Joe Carter of Savannah River. Based on the following scenario, KEI calculated a volume increase of 48 per cent for the SRP saltstone grouting process. For a salt-solution feed (concentrated HLW supernate and cesium; density 78.9 lb/ft³) of 78,000 lb/hr (composed of 52,000 lb/hr water; 989 ft³/hr), the quantity of liquid that goes to grouting after cesium removal is 105,600 lb/hr (composed of 77,700 lb/hr water; 1477 ft³/hr). Based on this information, KEI estimates the density of the grout feed to be 71.5 lb/ft³ [(105,600/77,700) x 78.9 / (78,000/52,000)]. The grouting process increases the 105,600 lb/hr (1477 ft³/hr) to 252,000 lb/hr (2188 ft³/hr), a volume increase of 48 per cent.

Vitrification

KEI assumes that the quantity of waste generated by the vitrification process is approximately the same as that for the NAG or 536,921 m³/20 years.

ANALYSIS RESULTS

The KEI life-cycle cost information presented in this section is site specific due to cost variations as a result of scale. KEI's analysis is based on the waste volume at the Hanford site, which has the largest amount of waste to be treated—one source estimates 600 million liters of aqueous nitrate waste—of any of the DOE sites.

A major component of the KEI life-cycle cost is what KEI refers to as the EG&G life-cycle cost. The WMFCI costing method of determining EG&G life-cycle costs is for planning level cost estimates having an accuracy of ± 30 per cent (for input flow rates within the range of the charts). Unfortunately, the throughputs assumed by KEI were not within the chart limits and, therefore, the EG&G life-cycle costs presented in this chapter are based on extrapolated data. Therefore, the level of accuracy is probably not as good. As a result, the estimates presented in this chapter are good for comparative alternative evaluations and should **not** be used to determine funding.

Overview

Figures 5, 6a, and 6b present KEI life-cycle cost comparisons for NAC/NAG/ NAX, vitrification, and grouting processes for treating alpha (10 nCi/g TRU) waste. The total life-cycle cost is comprised of facility construction, operating and maintenance, other (e.g., demonstration, studies, operations budget funded activities, decommissioning and decontamination, and credits), off-gas treatment (NOx for vitrification and ammonia for NAC/NAG/NAX), and disposal. Table 49 presents an overview of these data. Also refer to Appendix Table 3-2, which contains additional information. This appendix table groups the cost components into two categories—EG&G and other.

Table 50 is an overview of the equipment and building costs upon which Table 49 is based. Figure 5 is a total cost comparison for alpha waste assuming off-site disposal at Envirocare. Figure 6a compares those costs when disposal is at an on-site engineered disposal facility. Figure 6b is for on-site shallow land burial.

In addition to the EG&G cost components, a cost component or variable for each of the three treatment methods is on-site (engineered or shallow land) versus off-site (Envirocare)

disposal of the final waste product. Note that transportation costs for off-site disposal are the same for non-alpha and alpha as long as any radioactivity is present.

Grouting, which is the most straightforward treatment option to analyze, has no additional treatment variables.

A variable that is unique to vitrification is NO_x off-gas treatment costs. KEI evaluated the effect of vitrification off-gas treatment on costs assuming a high (\$6,000/ton NO_x) and a low value (\$1,000/ton NO_x). Note, however, that these costs assume the off-gas is not radioactive. A contaminated off-gas might require an even more expensive system.

NAC/NAG/NAX variables are final waste form, the cost of aluminum, and the disposition of ammonia. Final waste form options are to calcine the reaction product (NAC) or convert it to a glass waste form through vitrification (NAG). Another option is to solidify the uncalcined reaction product by reaction with a chemical such as lime (NAX). KEI assumed that the aluminum consumed in the process is government supplied and, therefore, applied a credit for the cost of aluminum. KEI applied no credit for ammonia sales because of the unlikelihood of such sales due to poor process economics.

Figures 7 and 10 present, respectively, overviews of the treatment cost per liter and the cost per gram-mole for each of the treatment methods assuming alpha waste. The costs are given for each of the three disposal options: on-site engineered, on-site shallow land, and off-site at Envirocare. Figures 8, 9a, and 9b present a detailed breakdown of the cost-per-liter data for each of the three disposal options while Figures 11, 12a, and 12b represent the cost-per-gmole data. Tables 51-52 summarize the data presented in these figures.

FIGURE 5. KEI LIFE-CYCLE COST (ALPHA, OFF-SITE)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 & \$6000/TON NO_x

FIGURE 6A. KEI LIFE-CYCLE COST (ALPHA, ON-SITE)

FIGURE 6B. KEI LIFE-CYCLE COST (ALPHA, ON-SITE)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 & \$6000/TON NO_x

FIGURE 7. COST PER LITER OVERVIEW (ALPHA PROCESS)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 AND \$6000/TON NO_x

FIGURE 8. COST PER LITER (ALPHA, OFF-SITE DISPOSAL)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 AND \$6000/TON NO_x

FIGURE 9A. COST PER LITER (ALPHA, ON-SITE DISPOSAL)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 AND \$6000/TON NO_x

FIGURE 9B. COST PER LITER (ALPHA, ON-SITE DISPOSAL)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 AND \$6000/TON NOx

FIG. 10. COST PER GMOLE OVERVIEW (ALPHA PROCESS)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 AND \$6000/TON NOx

FIGURE 11. COST PER GMOLE (ALPHA, OFF-SITE DISPOSAL)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 & \$6000/TON NO_x

FIGURE 12A. COST PER GMOLE (ALPHA, ON-SITE)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 & \$6000/TON NO_x

FIGURE 12B. COST PER GMOLE (ALPHA, ON-SITE)

NOTES: NAC/NAG/NAX: LOW & HIGH; VIT: \$1000 & \$6000/TON NOx

TABLE 49
KEI LIFE-CYCLE COST COMPARISON: NAC, NAG, NAX,
VITRIFICATION, AND GROUTING (ALPHA, 7000 HG/HR FACILITY)

	VITRIFICATION	GROUTING	NAC	
			LOW	HIGH
EG&G life-cycle*	5,368,837	566,898	738,996	1,148,973
Studies & tests	108,383	--	54,192	54,192
Demonstration	163,413	--	81,707	81,707
Facility construction	1,044,069	182,785	92,229	445,412
Operations funded	698,608	24,160	29,018	38,731
budget activities				
Operating & maint.	3,260,255	346,400	481,500	481,500
D&D	94,109	13,553	6,750	53,831
Process credits	---	---	(6,400)	(6,400)
Off-gas treatment (NOx)	125,345-752,074	---	---	---
Subtotal	5,494,182-6,120,911	566,898	738,996	1,148,973
Disposal				
Off-site: Envirocare	1,162,434	1,818,600	776,472	776,472
Transportation	24,698	38,640	16,497	16,497
Disposal fee	1,137,736	1,779,960	759,975	759,975
On-site: Shallow land	1,401,155	1,846,298	1,101,264	1,101,264
On-site: Engineered	2,726,240	3,541,520	2,141,422	2,141,422
TOTAL				
Off-site: Envirocare	6,656,616-7,283,345	2,385,498	1,515,468	1,925,445
On-site: Shallow land	6,895,337-7,522,066	2,413,196	1,840,260	2,250,237
On-site: Engineered	8,220,422-8,847,151	4,108,418	2,880,418	3,290,395

	NAG		NAX	
	LOW	HIGH	LOW	HIGH
EG&G life-cycle	2,275,354	2,685,856	1,135,538	1,546,042
Studies & tests	54,192	54,192	54,192	54,192
Demonstration	81,707	81,707	81,707	81,707
Facility construction	408,098	761,792	122,486	476,182
Operations funded	100,879	110,606	48,903	58,630
budget activities				
Operating & maint.	1,630,128	1,630,128	827,900	827,900
D&D	6,750	53,831	6,750	53,831
Process credits	(6,400)	(6,400)	(6,400)	(6,400)
Off-gas treatment (NOx)	---	---	---	---
Subtotal	2,275,354	2,685,856	1,135,538	1,546,042
Disposal				
Off-site: Envirocare	1,162,434	1,162,434	1,631,328	1,631,328
Transportation	24,698	24,698	34,661	34,661
Disposal fee	1,137,736	1,137,736	1,596,667	1,596,667
On-site: Shallow land	1,401,155	1,401,155	1,717,078	1,717,078
On-site: Engineered	2,726,240	2,726,240	3,340,934	3,340,934
TOTAL				
Off-site: Envirocare	3,437,788	3,848,290	2,766,866	3,177,370
On-site: Shallow land	3,676,509	4,087,011	2,852,616	3,263,120
On-site: Engineered	5,001,594	5,412,096	4,476,472	4,886,976

* Based on equipment and building cost data presented in Table 50.

Source: KEI

TABLE 50
EQUIPMENT AND BUILDING COST COMPARISON*

	VITRIFICA- TION	GROUT- ING	NAC	NAG	NAX
<u>Equipment Cost</u>^{1,2}	212098	41325	24635-56044	151835-183449	36820-68434
Prepare & feed incom- ing waste ^{1,2}	38787	18224	3225-28505	3225-28505	3225-28505
Melter	74760	NA	NA	74760	NA
Cool melter	3402	NA	NA	3402	NA
Prepare & feed soil	5920	NA	NA	NA	NA
Slag cooling & pkging.	23465	NA	NA	23465	NA
Air pollution control	44696	NA	NA	31733	NA
Prepare & feed caustic	4371	NA	NA	NA	NA
Electrical & control ^{1,2}	6371	904	904-3638	904-3638	904-3638
Utilities & mechani- cal ^{1,2}	4781	1174	1174-2978	1174-2978	1174-2978
Radiation monitoring ^{1,2}	2348	758	758-1553	758-1553	758-1553
Other equipment ^{1,2}	3197	1606	1606-2402	1606-2402	1606-2402
Store & feed binder	NA	2616	NA	NA	2616
Micro-solidification	NA	10292	NA	NA	10292
Drum capping & wash.	NA	6160	6160	NA	6160
Reactor ³	NA	NA	4875	4875	4875
Reaction-product hand- ing ³	NA	NA	4103	4103	3380
Miscellaneous ³	NA	NA	1744	1744	1744
Ammonia handling ³	NA	NA	86	86	86
NO _x control	⁴	NA	NA	NA	NA
<u>Building Cost</u>	215374	31271	12505-123323	12505-123118	12505-123118
TOTAL	552817-1149546	72596	37140-179367	164340-306567	49325-191552

* EG&G cost components only. Equipment and building cost form the basis for the EG&G life-cycle cost estimate presented in Appendix Table 3-2.

¹ High estimate is average of vitrification and grouting.

² Low estimate is KEI's estimate based on EG&G grouting data and/or MMES estimate.

³ Based on MMES estimate.

⁴ \$1000-6000/ton NO_x (\$125,345,000-752,074,000). Not included in the total because it is not included in EG&G life-cycle cost. NO_x control is a KEI life-cycle cost component.

Source: KEI

TABLE 51
KEI LIFE-CYCLE COST COMPARISON (\$/L): NAC, NAG, NAX,
VITRIFICATION, AND GROUTING (ALPHA, 7000 KG/HR FACILITY)

	VITRIFICATION	GROUTING	NAC	
			LOW	HIGH
EG&G life-cycle*	8.95	0.94	1.23	1.91
Studies & tests	0.18	0	0.09	0.09
Demonstration	0.27	0	0.14	0.14
Facility construction	1.74	0.30	0.15	0.74
Operations funded	1.16	0.04	0.05	0.06
budget activities				
Operating & maint.	5.43	0.58	0.80	0.80
D&D	0.16	0.02	0.01	0.09
Process credits	0	0	(0.01)	(0.01)
Off-gas treatment (NOx)	0.21-1.25	0	0	0
Disposal				
Off-site: Envirocare	1.94	3.03	1.29	1.29
Transportation	0.04	0.06	0.03	0.03
Disposal fee	1.90	2.97	1.27	1.27
On-site: Shallow land	2.34	3.08	1.84	1.84
On-site: Engineered	4.54	5.90	3.57	3.57
TOTAL				
Off-site: Envirocare	11.09-12.14	3.98	2.53	3.21
On-site: Shallow land	11.49-12.54	4.02	3.07	3.75
On-site: Engineered	13.70-14.75	6.85	4.80	5.48
	NAG		NAX	
	LOW	HIGH	LOW	HIGH
EG&G life-cycle	3.79	4.48	1.89	2.58
Studies & tests	0.09	0.09	0.09	0.09
Demonstration	0.14	0.14	0.14	0.14
Facility construction	0.68	1.27	0.20	0.79
Operations funded	0.17	0.18	0.08	0.10
budget activities				
Operating & maint.	2.72	2.72	1.38	1.38
D&D	0.01	0.09	0.01	0.09
Process credits	(0.01)	(0.01)	(0.01)	(0.01)
Off-gas treatment (NOx)	0	0	0	0
Disposal				
Off-site: Envirocare	1.94	1.94	2.72	2.72
Transportation	0.04	0.04	0.06	0.06
Disposal fee	1.90	1.90	2.66	2.66
On-site: Shallow land	2.34	2.34	2.86	2.86
On-site: Engineered	4.54	4.54	5.57	5.57
TOTAL				
Off-site: Envirocare	5.73	6.41	4.61	5.30
On-site: Shallow land	6.13	6.81	4.75	5.44
On-site: Engineered	8.34	9.02	7.46	8.14

* Based on equipment and building cost data presented in Table 50.

Source: KEI

TABLE 52
KEI LIFE-CYCLE COST COMPARISON (\$/GMOLE): NAC, NAG, NAX,
VITRIFICATION, AND GROUTING (ALPHA, 7000 KG/HR FACILITY)

	VITRIFICATION	GROUTING	NAC	
			LOW	HIGH
EG&G life-cycle*	2.06	0.21	0.27	0.43
Studies & tests	0.04	0	0.02	0.02
Demonstration	0.06	0	0.03	0.03
Facility construction	0.40	0.07	0.03	0.17
Operations funded	0.27	0.01	0.01	0.01
budget activities				
Operating & maint.	1.25	0.13	0.18	0.18
D&D	0.04	0	0	0.02
Process credits	0	0	0	0
Off-gas treatment (NOx)	0.05-0.29	0	0	0
Disposal				
Off-site: Envirocare	0.45	0.70	0.30	0.30
Transportation	0.01	0.01	0.01	0.01
Disposal fee	0.44	0.69	0.29	0.29
On-site: Shallow land	0.54	0.71	0.42	0.42
On-site: Engineered	1.05	1.36	0.82	0.82
TOTAL				
Off-site: Envirocare	2.56-2.80	0.91	0.57	0.73
On-site: Shallow land	2.65-2.89	0.92	0.69	0.85
On-site: Engineered	3.16-3.40	1.57	1.09	1.25
	NAG		NAX	
	LOW	HIGH	LOW	HIGH
EG&G life-cycle	0.88	1.03	0.44	0.59
Studies & tests	0.02	0.02	0.02	0.02
Demonstration	0.03	0.03	0.03	0.03
Facility construction	0.16	0.29	0.05	0.18
Operations funded	0.04	0.04	0.02	0.02
budget activities				
Operating & maint.	0.63	0.63	0.32	0.32
D&D	0	0.02	0	0.02
Process credits	0	0	0	0
Off-gas treatment (NOx)	0	0	0	0
Disposal				
Off-site: Envirocare	0.45	0.45	0.63	0.63
Transportation	0	0	0.01	0.01
Disposal fee	0.44	0.44	0.61	0.61
On-site: Shallow land	0.54	0.54	0.66	0.66
On-site: Engineered	1.05	1.05	1.29	1.29
TOTAL				
Off-site: Envirocare	1.33	1.48	1.07	1.22
On-site: Shallow land	1.42	1.57	1.10	1.25
On-site: Engineered	1.93	2.08	1.73	1.88

* Based on equipment and building cost data presented in Table 50.

Source: KEI

Grouting

The equipment layout for the EG&G grout stabilization module is shown in Figures 13a and 13b. This module is applicable to both alpha and non-alpha waste. It is composed of five main process unit operations that incorporate all buildings, systems, processes, equipment, devices, controls, and accessories required to prepare the incoming waste and stabilize it either by macro- or microencapsulation techniques.

Technical Basis and Assumptions

The large generator grouting process receives concentrated liquid waste and sludge via a pipeline. A chemical addition unit is used to adjust the chemistry of the feed before it is fed to the solidification unit operation. A preparation and feed unit (not necessary for liquid wastes) crushes and shreds incoming solid waste; the shredded waste is then collected in a storage hopper. Note that size reduction and preparation units (shredders) and solidification mixers are the major equipment capital cost items. Budgetary costs for the preparation and feed unit are based on vendor quotes for shredders, conveyors, and dust collection equipment. Solidification module assembly prices are based on quotes by Stock Equipment Co.

After encapsulation, the operator remotely moves the filled container to a capping and washing unit. This unit operation provides for sample collection, capping of the container, and removal of loose contamination from the container surface by high-pressure spray water jets. The containerized waste is ready for processing through radioassay and final certification, which are included in the back-end certification and shipping module.

Output consists mainly of drummed, solidified non-alpha and alpha waste. Waste water results from drum washing and treated off-gas is discharged to the atmosphere. Major O&M purchased materials, such as personal protective equipment, laboratory material, binder, and containers, are assumed to be consumable supplies, and their costs are estimated accordingly.

Cost Estimate

Refer back to Table 49 for an overview of the components that comprise KEI's life-cycle cost estimate. Appendix Tables 3-4 to 3-8 present a cost analysis of the large-facility cost data for LLW/MLLW non-alpha and alpha waste upon which KEI's extrapolated data for a 7,000 kg/hr system (Appendix Tables 3-9 to 3-10) were based.

Note: According to Joe Carter of Savannah River, a LLW grouting facility (non-shielded) was built there 7-8 years ago at a cost of approximately \$70 million. Note that this compares with KEI's non-alpha facility construction cost estimate of \$86.4 million.

EQUIPMENT LIST

- ① DRUM PUSHER
- ② INCOMING WASTE BIN
- ③ BIN HOIST
- ④ SHREDDER (2) WITH FEED HOPPER, DUST HOOD AND HYDRAULIC
- ⑤ AUGER FEEDER
- ⑥ WASTE TRANSFER BIN
- ⑦ UNDERBUNG CRANE IN ENCLOSED PROCESS AREA
- ⑧ LIVE BOTTOM BULK STORAGE HOPPER
- ⑨ AUGER FEEDER
- ⑩ DUST COLLECTOR, FAN AND HEPA FILTER
- ⑪ DRUM STAGING CONVEYOR (POWERED ROLL)
- ⑫ DRUM STAGING CONVEYOR (POWERED ROLL)
- ⑬ SOLIDIFICATION SYSTEM
- ⑭ DRUM CAPPING AND WASHING SYSTEM
- ⑮ RECEIVING TANK
- ⑯ PUMP
- ⑰ FILTER
- ⑱ ION EXCHANGE VESSELS
- ⑲ TREATED WASTE TANK
- ⑳ PUMP
- ㉑ SLUDGE TANK
- ㉒ PUMP
- ㉓ UNDERBUNG CRANE IN ENCLOSED MAINTENANCE AREA
- ㉔ HEPA FILTER AND FAN
- ㉕ STACK
- ㉖ BINDER STORAGE SILO
- ㉗ BLOWER
- ㉘ PNEUMATIC CONVEYOR
- ㉙ DAY BIN
- ㉚ DRUM STAGING CONVEYOR (GRAVITY)
- ㉛ PRECIPITATION TANK
- ㉜ ORGANIC REMOVAL FILTER VESSELS

FACILITY SIZE		DIMENSION IN FEET		DIMENSION IN METERS	
		A	B	A	B
LARGE GENERATOR	SMALL	40	100	12.2	30.5
	MEDIUM	50	109	15.2	33.2
	LARGE	60	127	18.3	38.7
SMALL GENERATOR	MINIMUM	-	-	-	-

Figure 13A Equipment layout for grout stabilization module (module GROUT).

Figure
13B

Process functional diagram for grout stabilization module (module GROUT).

Comparison with Another Cost Estimate

The following grouting estimate is based on a baseline rough order-of-magnitude estimate made by Jon Cruse of Westinghouse Hanford, which was based on the information contained in Table 53. This information in this table is for a 44-million gallon LLW grouting facility.

TABLE 53
GROUT FACTS

FACILITIES

1. **Dry Materials Facility**
 - Capacity (typical)
 - Portland cement—625 tons
 - Fly ash—625 tons
 - Attapulgate clay—250 tons
 - Indian red pottery clay—75 tons
 - Blended storage—320 tons
 - Operating blend rate—15 tons/hour
 - Design life—40 years
 - Cost—\$4 million capital
2. **Feed Tanks (AP-102)/(AP-104)**
 - Capacity—1,160,000 gal. of liquid waste
 - Design life—50 years
 - Cost—\$6 million each
 - Tank AP-104 planned to be on-line the end of 1991
3. **Grout Processing Module**
 - Maximum processing capacity—4 million gallons of waste feed per year
 - Normal processing rate—50 gpm
 - Time per grout campaign—18 days at 100% efficiency (35 days planned)
 - Cost—\$11 million capital
4. **Grout Disposal Vaults**
 - Capacity—1,400,000 gallons grout (125' long x 50' wide x 34' high)
 - \$5.5 million each (operating cost)
 - Construct 43 vaults to dispose of double-shell tank wastes

GROUT FORMULATION

1. **Phosphate/Sulfate Waste Formulation**
 - 19% Portland cement
 - 10% Fly ash
 - 5% Attapulgate clay
 - 4% Indian red pottery clay
 - 53% Liquid waste feed
2. **DST Waste Reference Formulation**
 - 18% Ground limestone
 - 13% Blast furnace slag
 - 13% Fly ash
 - 2% Portland cement
 - 54% Liquid waste feed
3. **Production Planned**
 - Start-up - August 1988 (PSW)
 - Mixed waste start-up - Sept. 1992
 - Years of operation - 25
 - Approximately 44,000,000 gallons of waste processed
4. **Grout Waste Disposal Cost**
 - \$15.00/gallon of waste
5. **Key Regulations**
 - DOE Order 5820.2/RL Order 5820.2A
 - DOE Order 6430.1A
 - WAC 173-303

**TABLE 53 (CONT.)
GROUT FACTS**

Miscellaneous

- Crew size—24 operators (12 PSW)
- Annual average operating budget (1990-1996)—\$40 million
- Number of RCRA ground water monitoring wells:
 - Installed 2/91: 8
 - Total planned by 9/93: 13

Source: Jon Cruse, Westinghouse Hanford

In this example, KEI based the calculations on 600 million liters (158 million gallons) of LLW Hanford waste. Because the baseline cost information used for comparison in this analysis is for a smaller facility, the costs will be scaled using the “6/10ths Rule.” Using this standard engineering method, a factor of 2.9 is obtained.

$$\begin{aligned}\text{Cost of Equip. A} &= \text{Cost of Equip. B} \times (\text{Cap. equip. A/Cap. equip. B})^{0.6} \\ \text{Cost A} &= \text{Grout cost B} \times (1.58 \times 10^8 / 4.4 \times 10^7)^{0.6} = 2.2 \times \text{Grout cost B}\end{aligned}$$

The design construction cost for the performance scenario can be obtained using this factor as follows:

$$\begin{aligned}\text{Dry materials facility} &= \$4,000,000 \times 2.2 = \$8,800,000 \\ \text{Grout processing module} &= \$11,000,000 \times 2.2 = \$24,200,000 \\ \text{Total capital cost} &= \$33,000,000\end{aligned}$$

Table 53 assumes a crew of 24 operators and a budget of \$40,000,000/yr for a 25-year operational life. Since our process is larger, assume operating costs follow the “6/10th rule”.

$$\begin{aligned}\$40,000,000 \times 2.2 &= \$88,000,000/\text{yr} \\ \$88,000,000 \times 25 &= \$2.20 \times 10^9 / 20 \text{ years}\end{aligned}$$

Assuming that grouting results in a 40 per cent volume increase, a vault having a capacity of 1,400,000 gallons will hold 1,000,000 gallons of feed. The number of vaults required and their cost are determined by the following:

$$\begin{aligned}\text{Number of vaults required} &= 1.58 \times 10^8 \text{ gallons total feed} / 1 \times 10^6 \text{ gallon capacity} = 158 \\ \text{Total vault cost} &= \$5,500,000 \times 158 = \$869,000,000\end{aligned}$$

The total volume to be disposed in 158 vaults is 221,200,000 gal (837,242 m³).

The cost per liter of aqueous waste treated = \$869,000,000 / 600,000,000 = \$1.45/liter, which does not include the cost of disposal.

Based on the performance scenario described earlier in this chapter, the sodium loading is: $9.9 \times 10^7 \text{ kg Na} / (158 \text{ vaults} \times 1.4 \times 10^6 \text{ gal/vault}) = 0.448 \text{ kg Na/gal}$.

Vitrification

The vitrification module, shown in Figures 14a and 14b, consists of twelve operations designed to convert the incoming waste into a leach-resistant, rock-like or glass-like material.

Technical Basis and Assumptions

The vitrification module processes non-combustible waste such as inorganic sludge, ash, soil, brick, concrete, and other similar material. The module can process solid waste of various shapes and forms. The size limitation imposed by the crusher/shredder is approximately 1 ft³ and the incoming waste can contain as much as 10 per cent combustibles.

In the solid-feed case, the resulting vitrified alpha and non-alpha waste, which is similar in composition to iron-enriched basalt, should meet both the land disposal restrictions and DOE disposal requirements. Off-gas is sent to the off-gas treatment unit operation.

Specific operations included in the EG&G cost estimate include an input waste preparation and feed unit that crushes and shreds the incoming waste and transfers it to a melter unit operation. At the melter unit operation, a predryer, operating at approximately 300-400°F, receives, dries, and feeds shredded waste and any sludge that must be vitrified to a vitrification furnace (or melter). The module is based on Retec's plasma torch furnace.

Soil is added to the melter through a soil storage and feed unit operation. The furnace melts the soil and waste to form a molten slag. [According to Ben Taheranian of Morrison Knudson, the amount of soil required to vitrify a liquid is around three times the liquid's volume.] A slag cooling and packaging unit is used to receive the molten slag from the melter and cast it into containers. Containers are then sealed and washed by high-pressure water to remove loose contamination from the container surface.

The melter is equipped with a secondary combustion unit that completes the volatile gas destruction. An induced air blower moves the secondary combustor effluent through the air pollution control device that is designed to remove particulates. A surge tank retains off-gas for reprocessing in the event of a process upset.

Major O&M purchased materials are consumables, such as personal protective equipment, laboratory material, binder, soil, and disposable containers. Incoming waste sizing and preparation (shredders), melter and its off-gas unit are the major equipment capital cost items. Cost for the preparation and feed unit are based on vendor quotes for shredders, conveyors, and dust collection equipment. Melter prices are based on budgetary quotes received from two vendors, Callidus Technologies and Retec. Callidus Technologies provided budgetary quotes for the various off-gas units.

There are several issues associated with using the EG&G module costs, which was primarily designed to handle solids, and the cost of one designed to handle liquids. In particular, the liquid system would not require shredders and other solid-handling equipment, but it would require holding tanks and possibly a filtration system. A system to slurry the liquid with soil would also be required. An important issue as a result of an aqueous feed is the generation of hydrogen, which would have to be addressed. The nitrates in the liquid could affect the costs, primarily in materials of construction. The materials used in the scrubbers, ceramic filters, and the NO_x abatement system might be affected. However, KEI assumed that the increased materials costs are offset by eliminating the solids-handling costs.

Although the EG&G costs are based on a system to glassify a waste stream that is primarily a solid, KEI assumed the costs are comparable to a liquid system. Personal communication with Peter Kong (INEL), who was referred to KEI as a vitrification expert by the WMFCI team, indicated that this was a reasonable assumption.

Cost Estimate

Refer back to Table 49 for an overview of the components that comprise KEI's life-cycle cost estimate. Appendix Tables 3-11 to 3-17 present a cost analysis of the large-facility cost data for LLW/MLLW non-alpha and alpha waste upon which KEI's extrapolated data for a 7,000 kg/hr system (Appendix Table 3-18) were based.

- EQUIPMENT LIST**
- ① SAMPLING SYSTEM
 - ② WASTE FEEDER
 - ③ MELTER
 - ④ PARTICULATE FILTER
 - ⑤ AFTERBURNER
 - ⑥ QUENCH COLUMN
 - ⑦ FILTER BAGHOUSE
 - ⑧ ACTIVATED CARBON FILTERS
 - ⑨ HEPA FILTERS
 - ⑩ FAN AND STACK
 - ⑪ COOLING CHAMBER
 - ⑫ CANISTER DECON
 - ⑬ INSPECT AND ASSAY
 - ⑭ OVERHEAD CRANE

FACILITY SIZE		DIMENSION IN FEET		DIMENSION IN METERS	
		A	B	A	B
LARGE GENERATOR	SMALL	80	214	24.4	65.2
	MEDIUM	100	180	30.5	54.9
	LARGE	120	196	36.6	59.8
SMALL GENERATOR	MINIMUM	—	—	—	—

Figure 14A Equipment layout for vitrification module (module VITRF).

Figure 14B Process functional diagram for vitrification module (module VITRF).

Nitrate to Ammonia and Ceramic or Glass (NAC/NAG/NAX)

This section provides an overview of KEI's NAC/NAG/NAX cost estimate. KEI's analysis is an attempt to place the 1992 MMES analysis on the same basis as the WMFCI-based estimates for grouting and vitrification. Note that the 1992 study assumed the feed was contact handleable, non-alpha waste. Refer to the section, *Performance Scenario*, presented earlier in this chapter for a discussion of the feed and the final waste product.

Refer to Appendix 4 for the assumptions and process parameters assumed in the 1992 study. While the 1992 estimate included a catalytic burner to convert the ammonia and hydrogen that is produced to nitrogen and water vapor, KEI assumed that the ammonia will be destroyed by scrubbing with dilute sulfuric acid. The cost of this burner was eliminated from KEI's analysis.

Raw Materials

Table 54 summarizes the annual and 20-year raw material feed rates, which are based on the flow chart shown in Figure 4. Aluminum metal, silica, and nitrogen gas are the principal raw materials required. The aluminum could be either raw aluminum metal ingot, recycled beverage cans, or contaminated aluminum scrap from various DOE sites.

In the 1992 analysis, 500 gallons per day of 50 per cent sodium hydroxide were required to adjust the feed pH. In the actual process, pH adjustment is not necessary because the tank waste is in the correct range. The 1992 analysis includes a catalytic burner, which needs around 10,000 ft³/min of unconditioned air. This is unnecessary if a scrubbing system is used.

TABLE 54
NAC/NAG/NAX RAW MATERIAL FEED RATES: ANNUAL AND 20-
YEAR

	ORNL SCALE (1 L/MIN FEED)		HANFORD SCALE (92 L/MIN FEED)	
	KG/YR	KG/20YR	KG/YR	KG/20YR
Silica (1.5 mole Si/mole Na)	126,197	2.5E+6	12E+6	2.4E+8
Aluminum	79,024	1.6E+6	7.3E+6	1.5E+8
Nitrogen	78,840	1.6E+6	7.3E+6	1.5E+8

Hourly feed rates: **Silica:** 24.02 kg/hr ORNL, 2,210 kg/hr Hanford; **Aluminum:** 15.035 kg/hr ORNL, 1,383 kg/hr Hanford. **Total:** 115.79 kg/hr ORNL and 10,654 Hanford, excluding the nitrogen purge (15 kg/hr, 200 L/min, ORNL; 1,380 kg/hr Hanford). [Based on 20-year processing period, around-the-clock operations 365 days/year with 60% availability or 5256 hr/yr.]

Source: KEI

Utilities

Power consumption is mainly for electrical loads for the pumps, feed tank heating, cooling tower fans and pumps, and agitator drives. Additional heat must be supplied for the product drier and calciner.

Reaction Product

Table 55 summarizes the annual and 20-year rates of reaction-product generation for the NAC/NAG/NAX process. Reaction products include ammonia; an off-gas containing nitrogen, hydrogen, and water; and the final solid waste form, which can take the form of a ceramic, a glass, or a glass-ceramic.

TABLE 55
NAC/NAG/NAX REACTION PRODUCT RATES: ANNUAL AND 20-YEAR

	ORNL SCALE (1 L/MIN FEED)		HANFORD SCALE (92 L/MIN FEED)	
	KG/YR	KG/20YR	KG/YR	KG/20YR
Off-gases				
Ammonia	17,319	3.5E+5	1.6E+6	3.2E+7
Nitrogen	78,840	1.6E+6	7.3E+6	1.5E+8
Water	5,046	100,915	464,105	9.3E+6
Hydrogen	804	16,083	74,110	1.5E+6
Final solid waste (post thermal processing)*				
Ceramic	72,313	1,446	6,652	133,040
Ceramic-glass	72,313	1,446	6,652	133,040
Glass	Unknown	Unknown	Unknown	

* Waste volume = 268,640 m³/20 yr. See Table 47 for information regarding the reaction product after it comes from the reactor (post centrifuging).

Based on 20-year processing period, around-the-clock operations 365 days/year with 60% availability or 5256 hr/yr.

Source: KEI adapted from ORNL data

Table 56 shows the composition of the centrifuged reaction product obtained from the NAC/NAG/NAX process prior to conversion to a glass or ceramic.

TABLE 56
COMPOSITION OF CENTRIFUGED NAC/NAG/NAX REACTION
PRODUCT (PRIOR TO CONVERSION TO GLASS OR CERAMIC)

COMPONENT	ORNL SCALE (1 LITER/ MIN), KG/HR *	HANFORD-SCALE (92 LITER/MIN), KG/HR **
H ₂ O	29.845	2,745.74
Al(OH) ₃	28.372	2,610.22
NaAlO ₂ •2.5H ₂ O	26.022	2,394.02
SiO ₂	24.01	2,208.92
Other Na salts	2.227	204.88
NaOH	0.89	81.88
NaNO	0.030	2.76
TOTAL	111.405	10,248.42

* This feed (obtained from ORNL DWG 93A-856) is 5 times the values from the ORNL material balance. Silica (24.02 kg/hr) and aluminum (15.035 kg/hr) are also added to the reactor. This is a feed total of 115.79 kg/hr, excluding the nitrogen purge (15 kg/hr, 200 L/min).

** In order to make the feed match that used for the 1992 NAC cost estimate, it is necessary to multiply the ORNL test feed presented in column 2 by 92 (460 times the values from the material balance).

Source: KEI adapted from ORNL data

Total Life-cycle Costs

The assumptions that went into KET's estimate of the EG&G life-cycle costs for the NAC/NAC/NAX processes are summarized in Table 57.

TABLE 57
NAC EG&G COST COMPONENT ASSUMPTIONS

COST COMPONENT	LOW	HIGH
1.0 Studies and bench-scale test costs*	50% of vitrification	50% of vitrification
1.1 Manpower costs during research	50% of vitrification	50% of vitrification
1.2 Equipment costs	50% of vitrification	50% of vitrification
1.3 Installation costs	50% of vitrification	50% of vitrification
1.4 Project management before Title I	10% of 1.1 to 1.3	10% of 1.1 to 1.3
1.5 Contingency	25% of 1.1 to 1.4	25% of 1.1 to 1.4
2.0 Demonstration costs*	50% of vitrification	50% of vitrification
2.1 Manpower costs during demonstration	50% of vitrification	50% of vitrification
2.2 Design cost	30% of 2.5	30% of 2.5
2.3 Inspection cost	7% of 2.5	7% of 2.5
2.4 Project management	10% of 2.5	10% of 2.5
2.5 Construction cost	50% of vitrification	50% of vitrification
2.5.1 Building structure cost	50% of vitrification	50% of vitrification
2.5.2 Equipment costs	50% of vitrification	50% of vitrification
2.5.3 Indirect	29% of 2.5.1 & 2.5.2	29% of 2.5.1 & 2.5.2
2.6 Construction management	17% of 2.5	17% of 2.5
2.7 Management reserve	10% of 2.5	10% of 2.5
2.8 Contingency	25% of 2.1 to 2.7	25% of 2.1 to 2.7
3.0 Production facility construction costs		
3.1 Design cost	12% of 3.4	12% of 3.4
3.2 Inspection cost	7% of 3.4	7% of 3.4
3.3 Project management	10% of 3.4	10% of 3.4
3.4 Construction cost		
3.4.1 Building structure costs	See Table 50	Avg. of vitrification & grouting
3.4.2 Equipment costs	See Table 50	Avg. of vitrification & grouting
3.4.3 Indirect	29% of 3.4.1 & 3.4.2	29% of 3.4.1 & 3.4.2
3.5 Construction management	17% of 3.4	17% of 3.4
3.6 Management reserve	10% of 3.4	10% of 3.4
3.7 Contingency	25% of 3.1 - 3.5	25% of 3.1 - 3.5

TABLE 57 (CONT.)
NAC EG&G COST COMPONENT ASSUMPTIONS

COST COMPONENT	LOW	HIGH
4.0 Operations budget funded activities		
4.1 Conceptual design	1.5% of 3.0	1.5% of 3.0
4.2 Safety assurance	1% of 3.0	1% of 3.0
4.3 NEPA permitting (\$6 mil. for EIS, \$1 mil for EA)		
4.4 Preparation for operations	100% of 5.0	100% of 5.0
4.5 Project management	10% of 4.1 to 4.4	10% of 4.1 to 4.4
5.0 Operating and maintenance costs		
5.1 Annual operating costs: operating and support labor, analytical, HP	1992 study	1992 study
5.2 Annual utility costs	1992 study	1992 study
5.3 Annual material costs		
5.3.1 Aluminum	16 mil lb/yr @ \$0.40/lb	16 mil lb/yr @ \$0.40/lb
5.3.2 Silica	25.5 mil. lb/yr @ \$35/ton	25.5 mil. lb/yr @ \$35/ton
5.3.3 Other supplies	1992 study	1992 study
5.4 Annual maintenance costs	1992 study	1992 study
5.5 Contingency	25% of 5.1 to 5.4	25% of 5.1 to 5.4
Subtotal		
Total 20-year O&M cost	20 times 5.0	20 times 5.0
6.0 Decontamination & decommissioning	\$450/ft ² building	Avg.of vitrification & grouting
7.0 Cost credits due to process savings		
Aluminum	16 mil lb/yr @ \$0/lb	16 mil lb/yr @ \$0/lb
Ammonia reuse	0	0

* Small relative to the other cost components.

Source: Based on information obtained by KEI from MK-Environmental and MMES' 1992 NAC cost estimate.

Equipment Costs

Table 58 summarizes the installed equipment costs as estimated by KEI. The assumptions behind these numbers are detailed in Table 59.

TABLE 58
NAC TOTAL INSTALLED EQUIPMENT COST

DESCRIPTION	NON-ALPHA, \$000			ALPHA, \$000		
	EQ. (C _E)	INST. (C _I)	TOT. (C _T)	EQ. (C _E)	INST. (C _I)	TOT. (C _T)
1.0 Prepare and feed incoming waste and raw materials	925	286	1210	2462	768	3225
Feed tank	50	10	60	100	16	116
Aluminum shredding system	259	53	312	566	108	674
Aluminum hopper	100	20	120	200	33	233
Aluminum feeder	150	31	181	300	57	357
Feed mixer	10	2	12	20	3	23
Feed heater	10	2	12	20	3	23
Allowance for piping/mech.	203	79	282	542	211	753
Allowance for elec./control	120	77	197	320	205	525
Calib., testing, & startup	22	12	34	59	33	92
Master-slave manipulator	0	0	0	59	14	73
Shield window	0	0	0	126	42	168
CCTV	0	0	0	27	6	33
Airlock	0	0	0	118	37	155
2.0 Reactor	1736	554	2291	3941	934	4875
Reactor vessel	500	102	602	1000	136	1136
Reactor cooler	500	102	602	1000	136	1136
Nitrogen feed controller	87	18	105	197	27	224
Allowance for piping/mech.	382	156	538	867	259	1126
Allowance for elec./control	226	151	377	512	252	764
Calib., testing, & startup	42	25	67	95	41	136
Shield windows	0	0	0	51	16	67
CCTV	0	0	0	22	5	27
Airlock	0	0	0	197	62	259
3.0 Reaction product-handling system	1150	366	1517	2965	1139	4103
Slurry feed pump	125	26	151	250	83	333
Reactor discharge pump	45	9	54	180	60	240
Sludge Dryer	150	31	181	300	61	361
Screw conveyors between dryer and calciner	100	20	120	200	50	250
Calciner	300	61	361	600	123	723
Allowance for piping/mech.	253	103	356	652	307	959
Allowance for elec./control	150	100	250	385	302	687
Calib., testing, & startup	28	16	44	71	47	118
Shield windows	0	0	0	151	50	201
CCTV	0	0	0	33	11	44
Airlock	0	0	0	142	45	187

TABLE 58 (CONT.)
NAC TOTAL INSTALLED EQUIPMENT COST

DESCRIPTION	NON-ALPHA, \$000			ALPHA, \$000		
	EQ. (C _E *)	INST. (C _I *)	TOT. (C _T *)	EQ. (C _E *)	INST. (C _I *)	TOT. (C _T *)
4.0 Miscellaneous						
Structural support	750	154	904	1500	244	1744
5.0 Ammonia-handling system	60	26	86	60	26	86
6.0 Electrical & control**	612	281	892	619	285	904
Control panel—FT						
Motor control center						
Standby emergency power						
Allowance for piping/mech.						
Allowance for elec./control						
Calib., testing, & startup						
7.0 Utilities & mechanical**	751	423	1174	751	423	1174
Instrument air package						
Compressed air package						
Breathing air package						
Service water						
Allowance for piping/mech.						
Allowance for elec./control						
Calib., testing, & startup						
8.0 HVAC						
Included with building costs						
9.0 Radiation monitoring**	459	211	670	583	175	758
Air monitors						
Area monitors						
Allowance for piping/mech.						
Allowance for elec./control						
Calib., testing, & startup						
10.0 Other equipment**	915	232	1147	1374	232	1606
Fire suppression system						
Emergency shower & decon station						
Sump pump system						
Allowance for piping/mech.						
Allowance for elec./control						
Calib., testing, & startup						
TOTAL	7358	2533	9891	14255	4226	18475

TABLE 58 (CONT.)
NAC TOTAL INSTALLED EQUIPMENT COST

* KEI first determined uninstalled equipment cost (C_E). Knowing this and the percentages summarized in Table 59, KEI calculated the installation costs. The sum of the equipment and installation costs is the total installed costs.

$C_I = X(C_T)$, where $X = \%$ (see Appendix Table 3-15)

Total installed equipment cost (C_T) = Equipment cost (C_E) + Installation cost (C_I)

$$C_T = C_E + X(C_T)$$

$$C_T = C_E / (1-X)$$

** For the low estimate, assumed to be the same as for a 7,000 grouting facility. For high estimate, assumed to be the average of vitrification and grouting.

Source: KEI

TABLE 59
NAC TOTAL INSTALLED EQUIPMENT COST ASSUMPTIONS

DESCRIPTION	NON-ALPHA			ALPHA		
	EQ. (%CAT) ¹	INST. (%TOT) ²	TOT.	EQ. (%CAT) ¹	INST. (%TOT) ²	TOT.
1.0 Prepare and feed incoming waste and raw materials	x=0.654 ³	---	Sum ⁴	x=0.740 ³	---	Sum ⁴
Feed tank	5a	17	"	5b	14	"
Aluminum shredding system	28	17	"	23	16	"
Aluminum hopper	5a	17	"	5b	14	"
Aluminum feeder	5a	17	"	5b	16	"
Feed mixer	5a	17	"	5b	14	"
Feed heater	5a	17	"	5b	14	"
Allowance for piping/mech.	22	28	"	22	28	"
Allowance for elec./control	13	39	"	13	39	"
Calib., testing, & startup	2.4	36	"	2.4	36	"
Master-slave manipulator	---	---	---	2.4	19	"
Shield window	---	---	---	5.1	25	"
CCTV	---	---	---	1.1	17	"
Airlock	---	---	---	1.1	24	"
2.0 Reactor	x=0.424 ³	---	Sum ⁴	x=0.493 ³	---	Sum ⁴
Reactor vessel	5a	17	"	5b	12	"
Reactor cooler	5a	17	"	5b	12	"
Nitrogen feed controller	5.0	17	"	5.0	12	"
Allowance for piping/mech.	22	29	"	22	23	"
Allowance for elec./control	13	40	"	13	33	"
Calib., testing, & startup	2.4	37	"	2.4	30	"
Shield windows	---	---	---	1.3	24	"
CCTV	---	---	---	0.55	17	"
Airlock	---	---	---	5.1	24	"
3.0 Reaction product-handling system	x=0.374 ³	---	Sum ⁴	x=0.484 ³	---	Sum ⁴
Slurry feed pump	5a	17	"	5b	25	"
Reactor discharge pump	5a	17	"	5b	25	"
Sludge Dryer	5a	17	"	5b	17	"
Screw conveyors between dryer and calciner	5a	17	"	5b	20	"
Calciner	5a	17	"	5b	17	"
Allowance for piping/mech.	22	29	"	22	32	"
Allowance for elec./control	13	40	"	13	44	"
Calib., testing, & startup	2.4	37	"	2.4	40	"
Shield windows	---	---	---	5.1	25	"
CCTV	---	---	---	1.1	25	"
Airlock	---	---	---	4.8	24	"

TABLE 59 (CONT.)
NAC TOTAL INSTALLED EQUIPMENT COST ASSUMPTIONS

DESCRIPTION	NON-ALPHA			EQ.	ALPHA	
	EQ. (%CAT) ¹	INST. (%TOT) ²	TOT.		INST. (%CAT) ¹	TOT. (%TOT) ²
4.0 Miscellaneous						
Structural support	5a	17	Sum ⁴	5b	14	Sum ⁴
5.0 Ammonia-handling system	6	30	"	6	30	"
6.0 Electrical & control	7	7	"	7	7	"
7.0 Utilities & mechanical	7	7	"	7	7	"
8.0 HVAC (Included with building costs)	---	---	---	---	---	---
9.0 Radiation monitoring	7	7	"	7	7	"
10.0 Other equipment	7	7	"	7	7	"
TOTAL	7	7	"	7	7	"

¹ Per cent of category total (e.g., 1.0, 2.0, etc.; see Appendix Table 3-16)

² Assumed percentages based on Appendix Table 3-15.

³ Category total (T) = sum of category 1992 study costs + 0.28T + 0.22T + 0.13T + 0.024T
= 1992 study costs + 0.654T
= 1992 study costs/(1-0.654), where 0.654=x

⁴ Sum of installed equipment and installation costs.

5a 1992 study.

5b 2 times 1992 study.

6 Industry sources.

7 For the low estimate, assumed to be the same cost as for a 7,000 kg/hr grouting facility. For high estimate, assumed to be the average of vitrification and grouting.

Source: KEI

Building Cost

Table 60 presents KEI's estimate for the NAC/NAG/NAX building cost. These figures are based on an analysis of the vitrification building cost data presented in Appendix Table 3-17.

TABLE 60
NAC/NAG/NAX BUILDING COST/AREA SUMMARY
(7,000 KG/HR FACILITY)

UNIT OPERATION	BUILDING AREA, FT²				TOTAL COST, \$
	ADMIN	MED. HAZ.	MAINT	ALPHA	
<u>LOW</u>					
Non-alpha	3500	3910	7590	0	8,344,200
Alpha	3500	4370	2185	4945	12,504,900
<u>HIGH</u>					
Avg. of vitrification & grouting					123,323,000

Source: KEI

Off-Gas Treatment

Off-gas treatments that are addressed by this study are 1) ammonia reuse or destruction and 2) NO_x abatement. Also briefly included in this discussion is technology for other potential emissions such as volatile metals, acid gases, or SO_x. Scrubbing technology is typically required for volatile metals, while a catalyst system different than that for NO_x is necessary for SO_x.

Ammonia. Refer back to Table 47 for a breakdown of the components of the off-gas produced by the NAC/NAG/NAX process. Note, however, that this off-gas contains water. Because an ammonia condensation system operates around -40°F, the water would freeze—fouling the heat exchanger that is used in the system. Unfortunately, separation of ammonia from water is difficult. Sorbents cannot be used to remove the water because, according to industry sources, the ammonia destroys these materials. Because of this, a scrubber is the best alternative for treating the ammonia/water-laden off-gas.

According to David Ming of Air Products, an elaborate scrubbing system (for non-radioactive off-gases) costs around \$50-60,000. A system using a dilute sulfuric acid/water solution can be used to destroy the ammonia and produce water, nitrogen, and salt (e.g., (NH₄)₂SO₄). After filtrating the salt, the stream can be discharged to the environment.

David also indicated that the economics of producing ammonia for reuse are terrible. If the NAC/NAG/NAX off-gas did not contain water, a condensation system could be used to generate a nitrogen/hydrogen product that Air Products currently sells for \$0.40/100 ft³.

Assuming 100 per cent of the ammonia produced by the NAC/NAG/NAX process is recovered, KEI estimates the quantity available for reuse is 303 kg/hr. Assuming 5,256

hr/yr, the total quantity of ammonia produced is 1.6 million kg/yr or 31.9 million kg/20 years.

NO_x. The vitrification cost-estimate includes an air pollution control system, which is made up of a wet and dry off-gas system. Personal communications with Ben Teheranian of Morrison Knudsen indicated that, assuming a scrubbing system could be made to work, a high-nitrate feed might require different materials of construction, increasing the cost. However, KEI assumed that the EG&G scrubber system would not be adequate to remove the NO_x emissions and that an NO_x system would be necessary in addition to the EG&G system.

Wet Scrubbing. KEI has received conflicting information regarding the use of wet scrubbing for NO_x removal. DOE sources indicate that it can be used successfully. However, according to the literature and pollution-industry sources, it is not effective for the concentrations mandated by the Clean Air Act.

Advantages of spray towers are that they are relatively inexpensive to install, operate, and maintain. They generally have low energy requirements (fan power of about 3×10^{-4} kW/acfm). Capital costs depend primarily on the cost of the vessel, the chemical treatment system, and the waste-water-treatment system. Operating expenses include waste water treatment costs, power requirements for pumps and fans, and chemical treatment for the scrubbing liquid. Waste water disposal cost is one item that strongly influences the economics of these towers. Costs may vary significantly, depending on site-specific factors.

Packed-bed scrubbers are more expensive to install and operate than spray towers. Like in spray towers, waste water disposal costs strongly influence the economics of these systems. In addition to pump and fan power requirements and chemical treatment for the scrubbing liquid, packing adds to the fixed costs of packed towers. As in spray towers, the liquid may be circulated to reduce makeup water costs.

Selective Catalytic Reduction. In Selective Catalytic Reduction (SCR) systems, the costs are site specific and can vary substantially due to variability in catalyst size, uncontrolled NO_x concentrations, NO_x reduction requirements, fuel properties, and ease of installation. Operating costs include catalyst replacement and disposal, ammonia consumption, and electricity. Electricity is used to overcome the pressure drop and ammonia vaporization across the system. Additional costs can include heat exchangers and possibly auxiliary fuel if flue-gas reheating is required.

David Ming of Air Products indicated that a system to handle 20-30 kg NO_x/hr is currently considered to be a large system. He has never seen one large enough to handle the NO_x that would result from vitrification of DOE's high-nitrate waste and questions whether one exists. [Note: Discussions with Engelhard, however, indicate that large systems have been produced.] Because vitrification operates at such a high temperature, a large percentage (possibly as high as 70%) of the nitrate in the feed would be emitted as NO_x as opposed to N₂ and O₂. Lower-temperature processes commonly result in 30-40 per cent NO_x emitted. Also note that the catalyst that is used to remove NO_x will not remove SO_x or volatile metals.

According to industry sources and published articles, the cost of NO_x removal systems is dropping rapidly. Before the stricter government regulations, there was little interest in controlling NO_x emissions and, as a result, the systems were expensive.

W.R. Grace Davison Chemical Division's newly developed catalyst has been reported to cut SCR reactor volumes by about one third and to increase time between catalyst changeovers. For new installations, the company indicates that this cuts costs to about \$870 per ton of NO_x removal as compared to \$2,170/ton for commercial systems now available. Costs for new systems are much higher than those for retrofits since new installations must conform to EPA's New Source Performance Standards (NSPS).

A 1990 capital-cost estimate for retrofitting industrial oil-fired boilers ranges from \$1.5 million for a 50-million-BTU/h unit to \$5 million for a 350-million-BTU/h system. A study sponsored by EPRI projects SCR capital costs to be \$78-93/kW for new coal-fired power plants. The estimate for retrofit to coal-fired units, depending on furnace type and reactor location, is \$96-140/kW. For retrofitting oil-fired boilers, the estimate is \$90-98/kW. For the coal-fired unit, about 20 per cent is attributed to retrofit-related costs and approximately 42 per cent for the SCR catalyst and reactor. Catalyst life, which is presently not known, dominates the cost. If lifetimes increase from two to four years, costs decrease by one third. California's SCAQMD estimated annual operating and maintenance costs are \$98,000-541,000 per year for boilers ranging from 50 million to 350 million BTU/h.

According to EPRI, projected costs, in constant 1990 dollars per ton of NO_x removed, vary widely with process conditions. These costs range from \$2,750 to almost \$4,000/ton NO_x for coal firing, and up to \$7,500/ton NO_x for oil firing at capacity factors above 50 per cent.

Radian Corp. claims that their Hybrid Low-NO_x system costs about three quarters as much to build as an SCR system. If waste heat is recovered, operating costs are also lower than SCR's.

Transportation and Disposal

The cost of disposal varies significantly according to the volume of waste that is disposed. KEI's cost estimate for on- and off-site (including transportation) disposal is summarized in Table 49 for the estimated levels of waste to be generated by NAC/NAG/NAX, vitrification, and grouting. Note that the cost of on-site disposal varies according to the quantity of waste to be disposed. The larger the waste volume, the smaller the unit cost. Refer to Appendix Table 3-2, section 15 for a detailed analysis of disposal cost.

In this study, KEI assumed that non-alpha material contains traces of radioactivity, which costs the same to ship as alpha material. Transportation costs via flat-bed truck (46,000 lb max/single stacking can hold 14 B-25 containers (90 ft³ each)/double stacking can hold 28) are based on the following quote from Kendrick Trucking of Harriman, TN:

Hanford to Envirocare:	\$1633 per load	Oak Ridge to Envirocare:	\$3822 per load
Hanford to Nevada:	\$2470 per load	Oak Ridge to Nevada:	\$4006 per load

Each load can be single or double stacked. A single-stack load carries 1260 ft³ or 35.7 m³ while a double-stacked load can carry 2520 ft³ or 71.4 m³.

Shallow-land Burial. Table 61 summarizes the data obtained by KEI regarding shallow-land-burial fees. Note that information regarding commercial fees is extremely difficult to obtain due to claims of proprietary information and secrecy agreements. Refer to Appendix Table 3-2, Sections 13, 14, and 15 for the cost to dispose of the final waste from the NAC/NAG/NAX, vitrification, and grouting processes by on-site (DOE location) and off-site (Envirocare) shallow land burial.

**TABLE 61
SHALLOW-LAND-BURIAL FEES**

LOCATION	SITE OPERATOR	DISPOSAL COST, \$/ft ³
DOE		
Nevada Test Site	Reynolds Electrical & Eng. Co.	6.77
Hanford	U.S. Ecology Co.*	70
COMMERCIAL		
Maxey Flats, KY	Nuclear Engineering	N/A
Beatty, NV	U.S. Ecology Co.*	N/A
Sheffield, IL	U.S. Ecology Co.*	N/A
Richland, WA	U.S. Ecology Co.*	N/A
Barnwell, SC	Chem-Nuclear Systems, Inc.	100-300**
West Valley, NY	Nuclear Fuel Services	N/A
Utah	Envirocare of Utah, Inc.	60

* Formerly Nuclear Engineering Co.

** \$100 for those in the compact, 300 for those who are not.

Source: KEI

DOE Sites. According to Bruce Becker of Reynolds Electrical & Engineering Co, the contractor that runs the Nevada Test Site disposal operations, the fee for LLW disposal at NTS is currently \$6.77/ft³. However, due to lower waste volume than anticipated, the actual fee should be around \$9.46/ft³. Bruce also estimated the cost for disposal at Hanford to be around \$70/ft³. Note that the NTS cost probably does not reflect total life-cycle costs. Refer to Appendix Table 3-2, Section 15, for a more accurate gauge of on-site life-cycle costs.

It has been published that the cost for disposal of contact-handled waste at INEL has historically ranged from \$50/ft³ (\$1,766/m³) for 100,000 ft³/yr (2,832 m³/yr) to \$150/ft³ (\$5,297/m³) for 25,000 ft³/year (708 m³/yr). Disposal costs have varied considerably because of varying annual disposal volumes. Site closure costs should be added to the shallow land disposal costs to obtain the total cost.

Commercial. According to Bruce Becker, the fee for LLW disposal at Barnwell is greater than \$100/ft³ for those in the compact and \$300 for those not in the compact. It is rumored that the cost of shallow-land disposal at Envirocare is less than at the NTS. However, according to Rick Korynta of DOE Oak Ridge Operations, the cost is \$60/ft³.

Geological Repository. Although the waste analyzed in this study is not high-level waste, fees for geological repository disposal are nevertheless included. These fees are expected to be different for different container types. The estimated costs for different containers are presented in Table 62, which was developed by personal communication between Westinghouse Hanford personnel and Bill Brocke, Roy F. Weston, Inc., Civilian Radioactive Waste Management Technical Support Team, Washington, D.C.

TABLE 62
REPOSITORY DISPOSAL FEE

CONTAINER	DISPOSAL FEE PER CONTAINER, \$	DISPOSAL FEE PER CUBIC FOOT, \$
0.62 m ³ (22 ft ³) canister	196,000	8,909
1.4 m ³ (49 ft ³) canister	217,000	4,429
11 m ³ (390 ft ³) canister	1,032,000	2,646

Source: *Tank Waste Technical Options Report*, Team leader: K.D. Boomer, Westinghouse Hanford Co. for the Dept. of Energy Office of Environmental Restoration and Waste Management, WHC-EP-0616 Rev. 0, March 31, 1993.

APPENDIX 1. LIST OF ABBREVIATIONS

ADU	Ammonium-Diuranate Process
ANS	American Nuclear Society
BAT	Best Available Technology
BHN	Brinell Hardness Number
CC	Complexant Concentrate
CFR	Code of Federal Regulations
CFM	Combustion-fired Melter
CSTR	Continuous Stirred Tank Reactor
D&D	Decontamination and Decommissioning
DOE	Department of Energy
DOT	Department of Transportation
DSS	Double-shell Slurry
DSSF	Double-shell Slurry Feed
DST	Double-shell Tanks
DWPF	Defense Waste Processing Facility
DWQC	National Primary Drinking Water Quality Criteria
EG&G	EG&G Idaho, Inc. (Note: used interchangeably with WMFCID)
EIX	Electrochemical Ion Exchange
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FEMP	Fernald Environmental Management Project
FEP	Fluorinated Ethylene-propylene Co-polymer
FTE	Full-time Equivalents
FR	Federal Register
FTE	Full-time Equivalent
GDP	Gaseous Diffusion Plant
HEME	High Efficiency Mist Eliminator
HEPA	High Efficiency Particulate Air filtration
HLW	High-level Waste
HTFW	High Temperature Fluid Wall
ICPP	Idaho Chemical Processing Plant
INEL	Idaho National Engineering Laboratory
KEI	KapLine Enterprises, Inc.
KMNC	Kerr-McGee Nuclear Corp.
LANL	Los Alamos National Laboratory
LFCM	Liquid-fed Ceramic Melter
LLW	Low-level Waste
M	Molar
MAWS	Minimum Additive Waste Stabilization
MCLG	Maximum Concentration Limit Guideline
MK	Morrison Knudsen Corp.
MLLW	Mixed low-level Waste
MMES	Martin Marietta Energy Systems
MVST	Melton Valley Storage Tank
NAC	Nitrate to Ammonia and Ceramic
NAG	Nitrate to Ammonia and Glass
NAX	Nitrate to Ammonia and Other Final Waste Form
NCAW	Neutralized Current Acid Waste
NCRW	Neutralized Cladding Removal Waste
NEPA	National Environmental Policy Act of 1969

APPENDIX 1. LIST OF ABBREVIATIONS (CONT.)

NO _x	Nitrogen Oxides
NRC	Nuclear Regulatory Commission
NSPS	New Source Performance Standards
NTS	Nevada Test Site
NWCF	New Waste Calcining Facility
O&M	Operations and Maintenance
ORNL	Oak Ridge National Laboratory
PCC	Portland Cement Concrete
PCF	Plasma Centrifugal Furnace
PEIS	Programmatic Environmental Impact Statement
PFP	Plutonium Finishing Plant
PLCC	Planning Life-cycle Cost
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene Fluoride
RCRA	Resource Conservation and Recover Act
RFNA	Red Fuming Nitric Acid
RFP	Rocky Flats Plant
SARF	Supercompactor and Repackaging Facility
SCAQMD	South Coast Air Quality Management District (California)
SCC	Stress Corrosion Cracking
SCR	Selective Catalytic Reduction
SCWO	Supercritical Water Oxidation
SPC	Sulfur Polymer Cement
SRP	Savannah River Plant
SST	Single-shell Tanks
SZP	Sodium Zirconium Phosphate
TCLP	Toxicity Characteristic Leaching Procedure
TRC	Thagard Research Corp.
TRU	Transuranic Elements
TSD	Treatment, Storage, and Disposal
UMTRA	Uranium Mill Tailings Remedial Action Project
UN	United Nations
VSL	Vitreous State Laboratory
WAC	Washington Administrative Code
WETF	West End Treatment Facility
WMFCI	Waste Management Facilities Cost Information Report (Note: used interchangeably with EG&G)
WNYNSC	Western New York Nuclear Service Center
WVPP	West Valley Pilot Project

APPENDIX 2. DEFINITION OF TERMS

Alpha mixed low-level waste: Contains transuranic nuclides at concentrations ranging from 10-100 nCi/g.

Anchor Facility: Denotes reference facilities that are either operating or are in advanced stages of design and construction.

Anchoring: Denotes using technical data and capital, operating and maintenance costs incurred by an anchor facility as a yardstick in the development of the planning level life-cycle cost estimates.

Glass, Borosilicate: A soda-lime glass, also known as Pyrex™, containing approximately 5 per cent boric oxide, which lowers the viscosity of the silica without increasing its thermal expansion. Such glasses have a very low expansion coefficient and high softening point (about 593°C). Tensile strength is about 10,000 psi. Continuous use temperature is 482°C.

Glass, Soda Lime: Consists of a uniformly dispersed mixture of silica (sand, 75%), soda ash (20%), and lime (5%), often combined with metallic oxides as those of calcium, lead, lithium, cerium, etc., depending on the specific properties desired. The blend or "melt" is heated to fusion temperature (approximately 700-800°C) and then gradually cooled (annealed) to a rigid, friable state, often referred to as vitreous. Technically, glass is an amorphous, undercooled liquid of extremely high viscosity, which has all the appearances of a solid. It has almost 100% elastic recovery. See Glass, Borosilicate.

Hazardous waste: Waste that might pose a potential hazard to human health or the environment if it is improperly treated, stored, transported, or disposed. Hazardous waste is regulated by two federal laws, or by the state.

High-level waste: Material that remains following the reprocessing of spent nuclear fuel and irradiated targets from reactors. This waste is highly radioactive and generates heat on its own. Some of its elements will remain radioactive for thousands of years. High-level waste must be managed very carefully and handled from behind heavy protective shielding.

Low-level waste: Waste that typically has small amounts of radioactivity in large amounts of material. Low-level waste is generated in every process involving radioactive materials. Most of the radioactivity in low-level waste will decay to harmless levels in a few years. Test specimens of fissionable material irradiated for R&D only, and not for the production of power or plutonium, may be classified as low-level waste, provided the concentration of transuranic is less than 100 nCi/g. For low-level-waste forms, the U.S. Nuclear Regulatory Commission (NRC) has prescribed a set of minimum requirements for physical stability. The NRC technical position includes requirements for strength, freeze-thaw cycling, irradiation, biodegradation, leaching, immersion, and freestanding liquids. In addition to these criteria, other degradation mechanisms specific to a waste form, such as combustion, are specified.

Mixed waste: Waste that contains both radioactive and hazardous materials.

Saltcrete: The solidified/stabilized product made using Portland cement and fly ash.

Sanitary waste: This waste is solid waste that does not contain radioactive, hazardous, or any specific contamination that is regulated.

Six-Tenths-Factor Rule: Cost of equip. $a = \text{cost of equip. } b (\text{capac. equip. } a / \text{capac. equip. } b)^{0.6}$.

Transuranic waste: Materials that are typically produced during reactor fuel assembly, nuclear weapons production, and fuel reprocessing. It contains manmade elements containing atomic numbers greater than that of uranium, which is 92. These elements generally decay slowly and require long-term isolation. This waste is not as intensively radioactive as high-level waste. Transuranic waste contains certain alpha-emitting radionuclides with half-lives greater than 20 years in concentrations greater than 100 nCi/g, regardless of source or form.

Uranium mill tailings: Naturally radioactive rock and soil that are products of uranium mining and milling operations. The rock and soil have low levels of radiation from the small amount of radium that decays and emits radon, a radioactive gas.

Waste management: Treating, storing, and disposing of the waste and spent nuclear fuel generated during weapons processing and manufacturing, research activities, and site cleanup activities.

APPENDIX 3. ESTIMATING PRINCIPLES AND KE'S ECONOMIC ANALYSIS DATA

ESTIMATING PRINCIPLES

The following information was obtained from *Perry's Chemical Engineers' Handbook* (6th Ed., 1984).

MANUFACTURING COSTS

Direct

Direct manufacturing costs include raw materials, operating labor, utilities, and some miscellaneous items. The cost of raw materials is normally the largest item of expense in the manufacturing cost of a product. The quantities of raw materials consumed can be calculated from material balances. The cost of operating labor is the second largest item of expense in the manufacturing cost. Labor requirements for a process can be estimated from an intelligent study of the equipment flow sheet, paying careful attention to the various primary steps such as fractionation, filtration, etc. Once the number of persons required per shift has been estimated for a particular production rate, the annual labor cost and the labor cost per unit of production can be estimated.

A study [*Chem. Eng.*, 59, 209-210 (July 1952)] of the operating-labor requirements in the U.S. chemical industry developed the following relationship of labor-hours per ton per processing step versus plant capacity in tons per day:

$$\log_{10} Y = 0.783 \log_{10} X + 1.252 + B$$

where Y is the operating-labor-hours per ton per processing step; X is plant capacity (tons per day), and B is a constant having values of 0.132 when multiple units are used to increase capacity or when the process is completely batch, of 0 for the average chemical-processing plant, and of -0.167 for large, highly automated plants or plants concerned with fluid processing.

The approximate cost of supervision for operating labor is equivalent to 10 per cent of the labor cost for simple operations and 25 per cent for complex operations.

The estimates for miscellaneous direct costs such as maintenance and repairs, operating supplies, royalties, and patents are best based on company records for similar processes. A rough average value for the annual cost of maintenance is 6 per cent of the capital cost of the plant. This percentage can vary from 2 to 10 per cent, depending on the severity of plant operation. Approximately half of the maintenance costs are for materials and half for labor. Royalty and patents costs are in the order of 1 to 5 per cent of the sales prices of the product.

Indirect

Indirect manufacturing costs include cost of payroll overhead, control laboratory, general plant overhead, packaging, and storage facilities. These estimates are best based on company records for similar processes.

Payroll overhead includes the cost of pensions, holidays, sick pay, etc., and is normally between 15 and 20 per cent of the operating-labor cost. Laboratory work is required for product quality control, and its cost is approximately 10 to 20 per cent of the operating-labor cost.

Plant overhead includes the cost of medical, safety, recreational, effluent-disposal, and warehousing facilities, etc. In general, the larger the plant, the lower the overhead per unit of production. Plant overhead costs can vary between 15 and 150 per cent of the operating-labor cost. Packaging costs depend on the physical and chemical nature of the product as well on its use and value. The cost of packaging is as high as one-third of the selling price for soaps and pharmaceuticals.

RAPID MANUFACTURING-COST ESTIMATES

The rapid manufacturing-cost estimating technique assumes that fixed manufacturing costs are a function of the fixed-capital investment and are independent of the production rate.

Property taxes or rates depend on location. They may be taken as 2 per cent of the fixed-capital cost of the plant in the absence of specific data. The cost of insurance depends on both location and the hazardous nature of the materials handled. This cost is normally on the order of 1 per cent of the fixed-capital cost of the plant. The manufacturing cost of a product is the sum of the processing or conversion cost and the cost of the raw materials. The processing cost can be roughly broken down into three parts: investment-related cost, labor-related cost, and utility cost.

Companies usually include in the charge for overhead the following items: operating supplies, supervision, indirect payroll expenses, plant protection, plant office, general plant overhead, and control laboratory. This overhead charge is frequently taken as an equivalent percentage of the direct labor cost.

The percentage is best obtained from company records. Although it can vary over a wide range, a typical value is 125 per cent. In this case, the labor-related cost would be 2.25 times the direct labor cost. For a 6,000-hour year and N persons per shift earning CL per hour, the annual labor-related cost would be $13,500 (CLN)$. According to DOE sources, the factor is 2.5-3.0. For the previous example, the annual labor-related cost for DOE would be $15,000 (CLN)$ to $18,000 (CLN)$.

If the annual property taxes are taken as $0.02 C_{FC}$, insurance as $0.01 C_{FC}$, and maintenance as $0.06 C_{FC}$, the annual investment-related cost would be $0.09 C_{FC}$, where C_{FC} is fixed-capital cost. Annual utilities cost is A_U . The annual processing cost A_P can be represented by the equation

$$A_P = \eta_1 C_{FC} + \eta_2 CLN + A_U$$

The annual processing cost A_{P2} for a similar plant of a different size designed for an annual production rate R_2 can be approximately calculated from an equation of the form

$$A_{P2} = \eta_1 C_{FC1} (R_2/R_1)^{0.7} + \eta_2 CLN_1 (R_2/R_1)^{0.25} + A_{U1} (R_2/R_1)$$

The processing cost per unit of production for a plant with an annual production R_2 can be approximately calculated from

$$A_{P2}/R_2 = 100/R_2 [\eta_1 C_{FC1} (R_2/R_1)^{0.7} + \eta_2 CLN_1 (R_2/R_1)^{0.25} + A_{U1} (R_2/R_1)]$$

KEI ANALYSIS DATA

The following information provided much of the basis for KEI's economic analysis. The 455 kg/hr vitrification facility and the 1,818 kg/hr grouting facility were the largest facility cost (sometimes referred to as upper-bound cost) data that KEI obtained from MK-Environmental.

Appendix Table 3-1 is an analysis of the data in terms of percentages, both of the segment and of the total. Appendix Table 3-2 provides an overview of KEI's analysis for 7,000 kg/hr facilities. EG&G vitrification and grouting life cycle costs are extrapolations of the data presented in Tables 3-2 to 3-3 and 3-8 to 3-9.

OVERVIEW

APPENDIX TABLE 3-1
COST COMPONENT ANALYSIS FOR EG&G DATA: VITRIFICATION
(455 KG/HR) AND GROUTING (1,818 KG/HR)

COST COMPONENT	% OF COST*			
	VITRIFICATION**		GROUTING	
	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA
1.0 Studies and bench-scale test costs	(1.22)	(0.61)	(0)	(0)
1.1 Manpower costs during research	56.9	56.9	0	0
1.2 Equipment costs	3.16	3.16	0	0
1.3 Installation costs	12.6	12.6	0	0
1.4 Project management before Title I	7.27	7.27	0	0
1.5 Contingency	20.0	20.0	0	0
2.0 Demonstration costs	(1.83)	(0.91)	(0)	(0)
2.1 Manpower costs during demonstration	50.3	50.3	0	0
2.2 Design cost	5.12	5.12	0	0
2.3 Inspection cost	1.19	1.19	0	0
2.4 Project management	1.70	1.70	0	0
2.5 Construction cost	17.0	17.0	0	0
2.5.1 Building structure cost	1.68	1.68	0	0
2.5.2 Equipment costs	11.5	11.5	0	0
2.5.3 Indirect	3.84	3.84	0	0
2.6 Construction management costs	2.91	2.91	0	0
2.7 Management reserve	1.70	1.70	0	0
2.8 Contingency	20.0	20.0	0	0
3.0 Production facility construction costs	(36.2)	(35.11)	(23.0)	(32.2)
3.1 Design cost	6.23	6.23	6.23	6.23
3.2 Inspection cost	3.63	3.63	3.63	3.63
3.3 Project management	5.19	5.19	5.19	5.19

APPENDIX TABLE 3-1 (CONT.)
COST COMPONENT ANALYSIS OF LIFE FOR EG&G DATA:
VITRIFICATION (455 KG/HR) AND GROUTING (1,818 KG/HR)

COST COMPONENT	% OF COST*			
	VITRIFICATION**		GROUTING	
	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA
3.4 Construction cost	51.9	51.9	51.9	51.9
3.4.1 Building structure costs	16.5	20.6	17.8	17.1
3.4.2 Equipment costs	23.8	19.6	22.4	23.1
3.4.3 Indirect	11.7	11.7	11.7	11.7
3.5 Construction management	8.88	8.88	8.88	8.88
3.6 Management reserve	5.19	5.19	5.19	5.19
3.7 Contingency	19.0	19.0	19.0	19.0
4.0 Operations budget funded activities	(3.90)	(4.03)	(4.47)	(4.25)
4.1 Conceptual design	13.9	13.0	7.72	11.4
4.2 Safety assurance	9.28	8.64	5.15	7.58
4.3 NEPA permitting (location operating cost)	0	0	0	0
4.4 Preparation for operations	67.7	69.3	78.0	72.0
4.5 Project management	9.09	9.09	9.09	9.09
5.0 Operating and maintenance costs				
5.1 Annual operating costs	49.4	30.7	27.5	29.8
5.2 Annual utility costs	2.94	1.38	0.876	0.683
5.3 Annual material costs	1.87	0.865	39.6	29.6
5.4 Annual maintenance costs	25.7	47.1	12.1	19.9
5.5 Contingency	20.0	20.0	20.0	20.0
5.6 Subtotal	2.64	2.82	3.49	3.06
5.7 Total 20-year O&M cost***	(52.8)	(56.31)	(69.8)	(61.2)
6.0 Decontamination & decommissioning	(4.08)	(3.00)	(2.75)	(2.40)
7.0 Pre-operations	(6.95)	(5.58)	(4.47)	(4.25)

* Numbers for main headings (i.e., 1.0, 2.0, 3.0, etc.), which are in parentheses, are per cent of EG&G life-cycle cost.

Subcomponents (i.e., 1.1, 2.1, 3.1, etc.) are per cent of main-heading cost components.

** KEI assumed NAC percentages to be the same as for vitrification.

*** Per cent of EG&G life-cycle cost.

Source: KEI

APPENDIX TABLE 3-2
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**	NAC (ALPHA)		NAG (ALPHA)		NAX (ALPHA)	
	LOW	HIGH	LOW	HIGH	LOW	HIGH
(\$000 unless otherwise noted)						
EG&G LIFE-CYCLE COMPONENTS						
1.0 Studies and bench-scale test costs	54,192	54,192	54,192	54,192	54,192	54,192
1.1 Manpower costs during research	---	---	---	---	---	---
1.2 Equipment costs	---	---	---	---	---	---
1.3 Installation costs	---	---	---	---	---	---
1.4 Project management before Title I	---	---	---	---	---	---
1.5 Contingency	---	---	---	---	---	---
2.0 Demonstration costs	81,707	81,707	81,707	81,707	81,707	81,707
2.1 Manpower costs during demonstration	---	---	---	---	---	---
2.2 Design cost	---	---	---	---	---	---
2.3 Inspection cost	---	---	---	---	---	---
2.4 Project management	---	---	---	---	---	---
2.5 Construction cost	---	---	---	---	---	---
2.5.1 Building structure cost	---	---	---	---	---	---
2.5.2 Equipment costs	---	---	---	---	---	---
2.5.3 Indirect	---	---	---	---	---	---
2.6 Construction management costs	---	---	---	---	---	---
2.7 Management reserve	---	---	---	---	---	---
2.8 Contingency	---	---	---	---	---	---
3.0 Production facility construction costs	92,229	445,412	408,098	761,792	122,486	476,182
3.1 Design cost	5,749	27,766	25,440	47,488	7,636	29,684
3.2 Inspection cost	3,354	16,197	14,840	27,702	4,454	17,316
3.3 Project management	4,791	23,138	21,200	39,574	6,363	24,737
3.4 Construction cost	47,911	231,383	211,999	395,736	63,629	247,367
3.4.1 Building structure costs	12,505	123,323	12,505	123,323	12,505	123,323
3.4.2 Equipment costs ¹	24,635	56,044	151,835	183,449	36,820	68,434
3.4.3 Indirect	10,771	52,016	47,659	88,964	14,304	55,610
3.5 Construction management	8,145	39,335	36,040	67,275	10,817	42,052
3.6 Management reserve	4,791	23,138	21,200	39,574	6,363	24,737
3.7 Contingency	17,488	84,455	77,379	144,444	23,225	90,289
4.0 Operations budget funded activities	29,018	38,731	100,879	110,606	48,903	58,630
4.1 Conceptual design	1,383	6,681	6,121	11,427	1,837	7,143
4.2 Safety assurance	922	4,454	4,081	7,618	1,225	4,762
4.3 NEPA permitting (location operating cost)	0	0	0	0	0	0
4.4 Preparation for operations	24,075	24,075	81,506	81,506	41,395	41,395
4.5 Project management	2,638	3,521	9,171	10,055	4,446	5,330
5.0 Operating and maintenance Costs/yr	24,075	24,075	81,506	81,506	41,395	41,395
5.1 Annual operating costs	8,980	8,980	---	---	---	---
5.2 Annual utility costs	375	375	---	---	---	---
5.3 Annual material costs	7,271	7,271	---	---	---	---
5.4 Annual maintenance costs	2,634	2,634	---	---	---	---
5.5 Contingency	4,815	4,815	---	---	---	---
5.6 Total 20-year O&M cost	481,500	481,500	1,630,128	1,630,128	827,900	827,900
6.0 Decontamination & decommissioning (450/ft² except for NAC-High, which is average of vitrification and grouting)	6,750	53,831	6,750	53,831	6,750	53,831
7.0 Process credits	(6,400)	(6,400)	(6,400)	(6,400)	(6,400)	(6,400)
7.1 Scrap aluminum consumption ²	(6,400)	(6,400)	(6,400)	(6,400)	(6,400)	(6,400)
7.2 Ammonia reuse ³	(0)	(0)	(0)	(0)	(0)	(0)

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**	VITRIFICATION		GROUTING	
	NON- ALPHA	ALPHA	NON- ALPHA	ALPHA
EG&G LIFE-CYCLE COMPONENTS				
1.0 Studies and bench-scale test costs	108,383	108,383	0	0
1.1 Manpower costs during research	61,678	61,678	0	0
1.2 Equipment costs	3,427	3,427	0	0
1.3 Installation costs	13,706	13,706	0	0
1.4 Project management before Title I	7,881	7,881	0	0
1.5 Contingency	21,690	21,690	0	0
2.0 Demonstration costs	163,413	163,413	0	0
2.1 Manpower costs during demonstration	82,238	82,238	0	0
2.2 Design cost	8,361	8,361	0	0
2.3 Inspection cost	1,953	1,953	0	0
2.4 Project management	2,776	2,776	0	0
2.5 Construction cost	27,858	27,858	0	0
2.5.1 Building structure cost	2,741	2,741	0	0
2.5.2 Equipment costs	18,846	18,846	0	0
2.5.3 Indirect	6,271	6,271	0	0
2.6 Construction management costs	4,763	4,763	0	0
2.7 Management reserve	2,776	2,776	0	0
2.8 Contingency	32,690	32,690	0	0
3.0 Production facility construction costs	545,188	1,044,069	86,403	182,785
3.1 Design cost	33,965	65,040	5,382	11,388
3.2 Inspection cost	19,810	37,944	3,140	6,643
3.3 Project management	28,302	54,204	4,486	9,489
3.4 Construction cost	283,036	542,019	44,854	94,845
3.4.1 Building structure costs	89,873	215,374	15,379	31,271
3.4.2 Equipment costs ¹	129,535	204,794	19,391	42,242
3.4.3 Indirect	63,628	121,851	10,084	21,333
3.5 Construction management	48,397	92,684	7,670	16,226
3.6 Management reserve	28,302	54,204	4,486	9,489
3.7 Contingency	103,377	197,973	16,384	34,660
4.0 Operations budget funded activities	347,523	698,608	16,532	24,160
4.1 Conceptual design	48,349	90,819	1,276	2,754
4.2 Safety assurance	32,244	60,360	851	1,831
4.3 NEPA permitting (location operating cost)	0	0	0	0
4.4 Preparation for operations	235,337	484,136	12,894	17,395
4.5 Project management	31,593	63,503	1,503	2,196
5.0 Operating and maintenance costs/yr	76,049	163,013	12,775	17,320
5.1 Annual operating costs	37,593	50,055	3,509	5,156
5.2 Annual utility costs	2,237	2,243	112	118
5.3 Annual material costs	1,428	1,410	5,054	5,133
5.4 Annual maintenance costs	19,577	76,704	1,544	3,449
5.5 Contingency	15,214	32,600	2,556	3,464
5.6 Total 20-year O&M cost (NAC + grout)	1,520,984	3,260,255	255,495	346,400
6.0 Decontamination & decommissioning (450/ft ² except for NAX-High, which is average of vitrification and grouting)	66,437	94,109	10,015	13,553
7.0 Process credits	(0)	(0)	(0)	(0)
7.1 Scrap aluminum consumption ²	(0)	(0)	(0)	(0)
7.2 Ammonia reuse ³	(0)	(0)	(0)	(0)

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**		NAC/NAG/NAX		VITRIFICATION		GROUTING	
		(ALPHA)					
		LOW	HIGH	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA
(\$000 unless otherwise noted)							
8.0	EG&G 20-year life-cycle cost ^{4,5,6} : NAC, vitrification ⁶ , grouting	738,996	1,148,973	2,751,929	5,368,837	368,445	566,898
	\$/L	1.23	1.91	4.59	8.95	0.61	0.94
	\$/gmole Na	0.28	0.44	1.06	2.06	0.14	0.22
9.0	EG&G 20-year life-cycle cost ⁴ : NAG	2,275,354	2,685,856	Not applicable		Not applicable	
	\$/L	3.79	4.48	"		"	
	\$/gmole	0.88	1.03	"		"	
10.0	EG&G 20-year life-cycle cost ⁴ : NAX	1,135,538	1,546,042	Not applicable		Not applicable	
	\$/L	1.89	2.58	"		"	
	\$/gmole	0.44	0.59	"		"	
ADDITIONAL COMPONENTS							
11.0	NO _x off-gas for high nitrate feed (vitrification only) ⁷						
11.0a	\$1000/ton NO _x	Not applicable		125,345	125,345	Not applicable	
11.0b	\$6000/ton NO _x	"		752,074	752,074	"	
12.0	Transportation to off-site disposal ⁸	NON-ALPHA	ALPHA				
12.1	NAC/Vitrification/Grouting						
12.1a	Single stacked on flat-bed truck						
12.1a.1	Hanford to Nevada,\$69/m³	24,747	24,747	37,048	37,048	57,960	57,960
12.1a.2	Hanford to Enviro.,\$46/m³	16,497	16,497	24,698	24,698	38,640	38,640
12.1a.3	Oak Ridge to Nev.,\$112/m³	Priced for comparison only		Priced for comparison only		Priced for comparison only	
12.1b	Double stacked on flat-bed truck						
12.1b.1	Hanford to Nevada,\$35/m³	12,553	12,553	18,792	18,792	59,400	59,400
12.1b.2	Hanford to Enviro.,\$23/m³	8,249	8,249	12,349	12,349	19,320	19,320
12.1b.3	Oak Ridge to Nev.,\$56/m³	Priced for comparison only		Priced for comparison only		Priced for comparison only	
12.2	NAG						
12.2a	Single stacked on flat-bed truck						
12.2a.1	Hanford to Nevada,\$69/m³	37,048	37,048	Not applicable		Not applicable	
12.2a.2	Hanford to Enviro.,\$46/m³	24,698	24,698	"		"	
12.2a.3	Oak Ridge to Nev.,\$112/m³	Priced for comparison only		"		"	
12.2b	Double stacked on flat-bed truck						
12.2b.1	Hanford to Nevada,\$35/m³	18,792	18,792	"		"	
12.2b.2	Hanford to Enviro.,\$23/m³	12,349	12,349	"		"	
12.2b.3	Oak Ridge to Nev.,\$56/m³	Priced for comparison only		"		"	
12.3	NAX						
12.3a	Single stacked on flat-bed truck						
12.3a.1	Hanford to Nevada,\$69/m³	51,992	51,992	Not applicable		Not applicable	
12.3a.2	Hanford to Enviro.,\$46/m³	34,661	34,661	"		"	
12.3a.3	Oak Ridge to Nev.,\$112/m³	Priced for comparison only		"		"	
12.3b	Double stacked on flat-bed truck						
12.3b.1	Hanford to Nevada,\$35/m³	26,373	26,373	"		"	
12.3b.2	Hanford to Enviro.,\$23/m³	17,331	17,331	"		"	
12.3b.3	Oak Ridge to Nev.,\$56/m³	Priced for comparison only		"		"	

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**	NAC/NAG/NAX		VITRIFICATION		GROUTING	
	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA
(\$000 unless otherwise noted)						
ADDITIONAL COMPONENTS						
(CONT.)						
13.0 Disposal fee (off-site): 20-year costs^{9,10}						
13.1 NAC/Vitrification/Grouting						
13.1a Nevada Test Site (\$7/ft ³ , \$247/m ³)	88,586	88,586	132,619	132,619	207,480	207,480
13.1b Hanford (\$70/ft ³ , \$2472/m ³)	886,578	886,578	1,327,269	1,327,269	2,076,480	2,076,480
13.1c Barnwell (\$100/ft ³ , \$3531/m ³ in compact; \$300 /ft ³ , \$10,594/m ³ out)	1,266,386/	1,266,386/	1,895,868/	1,895,868/	2,966,040	2,966,400/
13.1d Envirocare (\$60/ft ³ , \$2,119/m ³)	3,799,517	3,799,517	5,688,141	5,688,141	8,899,199	8,899,199
13.2 NAG	759,975	759,975	1,137,736	1,137,736	1,779,960	1,779,960
13.2a Nevada Test Site (\$7/ft ³ , \$247/m ³)	132,619	132,619	Not applicable		Not applicable	
13.2b Hanford (\$70/ft ³ , \$2472/m ³)	1,327,269	1,327,269	"		"	
13.2c Barnwell (\$100/ft ³ , \$3531/m ³ in compact; \$300 /ft ³ , \$10,594/m ³ out)	1,895,868/	1,895,868/	"		"	
13.2d Envirocare (\$60/ft ³ , \$2,119/m ³)	5,688,141	5,688,141	"		"	
13.3 NAX	1,137,736	1,137,736	"		"	
13.3a Nevada Test Site (\$7/ft ³ , \$247/m ³)	186,115	186,115	Not applicable		Not applicable	
13.3b Hanford (\$70/ft ³ , \$2472/m ³)	1,862,652	1,862,652	"		"	
13.3c Barnwell (\$100/ft ³ , \$3531/m ³ in compact; \$300 /ft ³ , \$10,594/m ³ out)	2,660,609/	2,660,609/	"		"	
13.3d Envirocare (\$60/ft ³ , \$2,119/m ³)	7,982,579	7,982,579	"		"	
	1,596,667	1,596,667	"		"	
14.0 Disposal (on-site): 20-year costs¹¹						
14.1 NAC/Vitrification/Grouting						
14.1a Engineered	2,141,422	2,141,422	2,726,240	2,726,240	3,541,520	3,541,520
14.1a.1 Front-end	300,775	300,775	381,388	381,388	498,872	498,872
14.1a.2 Facility construc.	779,436	779,436	992,946	992,946	1,292,688	1,292,688
14.1a.3 O&M (20 year)	819,203	819,203	1,043,606	1,043,606	1,349,131	1,349,131
14.1a.4 Pre-operations	176,036	176,036	224,257	224,257	291,656	291,656
14.1a.5 D&D	65,972	65,972	84,043	84,043	109,177	109,177
14.1b Shallow land	1,101,264	1,101,264	1,401,155	1,401,155	1,846,298	1,846,298
14.1b.1 Front-end	300,775	300,775	381,388	381,388	498,872	498,872
14.1b.2 Facility construc.	34,804	34,804	44,338	44,338	56,062	56,062
14.1b.3 O&M (20 year)	580,064	580,064	738,961	738,961	982,057	982,057
14.1b.4 Pre-operations	34,804	34,804	44,338	44,338	57,995	57,995
14.1b.5 D&D	150,817	150,817	192,130	192,130	251,314	251,314
14.2 NAG						
14.2a Engineered	2,726,240	2,726,240	Not applicable		Not applicable	
14.2a.1 Front-end	381,388	381,388	"		"	
14.2a.2 Facility construc.	992,946	992,946	"		"	
14.2a.3 O&M (20 year)	1,043,606	1,043,606	"		"	
14.2a.4 Pre-operations	224,257	224,257	"		"	
14.2a.5 D&D	84,043	84,043	"		"	
14.2b Shallow land	1,401,155	1,401,155	"		"	
14.2b.1 Front-end	381,388	381,388	"		"	
14.2b.2 Facility construc.	44,338	44,338	"		"	
14.2b.3 O&M (20 year)	738,961	738,961	"		"	
14.2b.4 Pre-operations	44,338	44,338	"		"	
14.2b.5 D&D	192,130	192,130	"		"	

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**	NAC/NAG/NAX		VITRIFICATION		GROUTING	
	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA
(\$000 unless otherwise noted)						
ADDITIONAL COMPONENTS						
(CONT.)						
14.0 Disposal (on-site): 20-year costs						
(Cont.) ¹¹						
14.3 NAX						
14.3a	Engineered	3,340,934	3,340,934	Not applicable	Not applicable	
14.3a.1	Front-end	467,381	467,381	"	"	
14.3a.2	Facility construc.	1,216,828	1,216,828	"	"	
14.3a.3	O&M (20 year)	1,278,911	1,278,911	"	"	
14.3a.4	Pre-operations	274,821	274,821	"	"	
14.3a.5	D&D	102,993	102,993	"	"	
14.3b	Shallow land	1,717,078	1,717,078	"	"	
14.3b.1	Front-end	467,381	467,381	"	"	
14.3b.2	Facility construc.	54,335	54,335	"	"	
14.3b.3	O&M (20 year)	905,577	905,577	"	"	
14.3b.4	Pre-operations	54,335	54,335	"	"	
14.3b.5	D&D	235,450	235,450	"	"	
DISPOSAL COST ANALYSIS						
15.0 Disposal costs ^{10,12} : \$/ft ³ (off-site costs include single-stack transportation)						
15.1 NAC/Vitrification/Grouting						
15.1a	On-site					
15.1a.1	Engineered	169	169	143	143	119
	O&M (20 year)	65	65	55	55	45
	Facility construc.	62	62	52	52	44
	Front-end	24	24	20	20	17
	Pre-operations	14	14	12	12	10
	D&D	5	5	4	4	4
15.1a.2	Shallow land	87	87	74	74	62
	O&M (20 year)	46	46	39	39	33
	Front-end	24	24	20	20	17
	D&D	12	12	10	10	8
	Pre-operations	3	3	2	2	3
	Facility construc.	3	3	2	2	2
15.1b	Off-site					
15.1b.1	Envirocare	61	61	61	61	61
15.1b.2	Nevada Test Site (NTS)	9	9	9	9	9
15.2 NAG						
15.2a	On-site					
15.2a.1	Engineered	143	143	Not applicable	Not applicable	
	O&M (20 year)	55	55	"	"	
	Facility construc.	52	52	"	"	
	Front-end	20	20	"	"	
	Pre-operations	12	12	"	"	
	D&D	4	4	"	"	
15.2a.2	Shallow land	74	74	"	"	
	O&M (20 year)	39	39	"	"	
	Front-end	20	20	"	"	
	D&D	10	10	"	"	
	Facility construc.	2	2	"	"	
	Pre-operations	2	2	"	"	

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**		NAC/NAG/NAX		VITRIFICATION		GROUTING	
		NON-ALPHA	ALPHA	NON-ALPHA	ALPHA	NON-ALPHA	ALPHA
		(\$000 unless otherwise noted)					
DISPOSAL COST ANALYSIS (CONT.)							
15.0 Disposal costs ^{10,12} ; \$/ft ³ (off-site costs include single-stack transportation)							
15.2 NAG (Cont.)							
15.2b Off-site							
15.2b.1 Envirocare		Same as NAC		Not applicable		Not applicable	
15.2b.2 NTS		"		"		"	
15.3 NAX							
15.3a On-site							
15.3a.1 Engineered		126	126	Not applicable		Not applicable	
O&M (20 year)		48	48	"		"	
Facility construc.		46	46	"		"	
Front-end		18	18	"		"	
Pre-operations		10	10	"		"	
D&D		4	4	"		"	
15.3a.2 Shallow land		65	65	"		"	
O&M (20 year)		34	34	"		"	
Front-end		18	18	"		"	
D&D		9	9	"		"	
Facility construc.		2	2	"		"	
Pre-operations		2	2	"		"	
15.3b Off-site							
15.3b.1 Envirocare		Same as NAC		Not applicable		Not applicable	
15.3b.2 NTS		"		"		"	
TOTAL LIFE-CYCLE COSTS		ALPHA					
		LOW	HIGH				
16.0 KEP's 20-year life-cycle costs, \$							
16.1 NAC							
16.1a On-site disposal (8.0 + 14.1)							
16.1a.1 Engineered disposal		2,880,418	3,290,395	Not applicable		Not applicable	
16.1a.2 Shallow-land disposal		1,840,260	2,250,237	"		"	
16.1b Off-site disposal: Envirocare (8.0 + 12.1a.2 + 13.1d)		1,515,468	1,925,445	"		"	
16.2 NAG							
16.2a On-site disposal (9.0 + 14.2)							
16.2a.1 Engineered disposal		5,001,594	5,412,096	Not applicable		Not applicable	
16.2a.2 Shallow-land disposal		3,676,509	4,087,011	"		"	
16.2b Off-site disposal: Envirocare (9.0 + 12.2a.2 + 13.2d)		3,437,788	3,848,290	"		"	
16.3 NAX							
16.3a On-site disposal (10.0 + 14.3)							
16.3a.1 Engineered disposal		4,476,472	4,886,976	Not applicable		Not applicable	
16.3a.2 Shallow-land disposal		2,852,616	3,263,120	"		"	
16.3b Off-site disposal: Envirocare (10.0 + 12.3a.2 + 13.3d)		2,766,866	3,177,370	"		"	
16.4 Vitrification							
16.4a \$1000/ton NO _x							
16.4a.1 On-site disposal (8.0 + 11.0a + 14.1)							
Engineered disposal		Not applicable		5,603,514	8,220,422	Not applicable	
Shallow-land disposal		"		4,278,429	6,895,337	"	
16.4a.2 Off-site disposal: Enviro. (8.0 + 11.0a + 12.2 + 13.2)		"		4,039,708	6,656,616	"	

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**	NAC/NAG/NAX (ALPHA)		VITRIFICATION		GROUTING	
	LOW	HIGH	NON- ALPHA	ALPHA	NON- ALPHA	ALPHA
(\$000 unless otherwise noted)						
TOTAL LIFE-CYCLE COSTS						
(CONT.)						
16.0 KEI's 20-year life-cycle costs (Cont.)						
16.4 Vitrification (Cont.)						
16.4b \$6000/ton NO _x						
16.4b.1 On-site disposal (8.0 + 11.0b + 14.1)						
Engineered disposal	Not applicable		6,230,243	8,847,151	Not applicable	
Shallow-land disposal	"		4,905,158	7,522,066	"	
16.4b.2 Off-site disposal: Enviro- care (8.0 + 11.0b + 12.2a.2 + 13.2d)	"		4,666,437	7,283,345		
16.5 Grouting						
16.5a On-site disposal (8.0 + 14.1)						
16.5a.1 Engineered disposal	Not applicable		Not applicable		3,909,965	4,108,418
16.5a.2 Shallow-land disposal	"		"		2,214,743	2,413,196
16.5b Off-site disposal: Envirocare (8.0 + 12.1a.2 + 13.1d)	"		"		2,166,666	2,365,119
17.0 \$/liter aqueous waste treated over 20 years (KEI Life-cycle cost/600 mil L)						
17.1 NAC						
17.1a On-site disposal						
17.1a.1 Engineered disposal	4.80	5.48	Not applicable		Not applicable	
17.1a.2 Shallow-land disposal	3.07	3.75	"		"	
17.1b Off-site disposal: Envirocare	2.53	3.21	"		"	
17.2 NAG						
17.2a On-site disposal						
17.2a.1 Engineered disposal	8.34	9.02	Not applicable		Not applicable	
17.2a.2 Shallow-land disposal	6.13	6.81	"		"	
17.2b Off-site disposal: Envirocare	5.73	6.41	"		"	
17.3 NAX						
17.3a On-site disposal						
17.3a.1 Engineered disposal	7.46	8.14	Not applicable		Not applicable	
17.3a.2 Shallow-land disposal	4.75	5.44	"		"	
17.3b Off-site disposal: Envirocare	4.61	5.30	"		"	
17.4 Vitrification						
17.4a \$1000/ton NO _x						
17.4a.1 On-site disposal						
Engineered disposal	Not applicable		9.34	13.70	Not applicable	
Shallow-land disposal	"		7.13	11.49	"	
17.4a.2 Off-site disposal: Enviro	"		6.73	11.09	"	
17.4b \$6000/ton NO _x						
17.4b.1 On-site disposal						
Engineered disposal	"		10.38	14.75	"	
Shallow-land disposal	"		8.18	12.54	"	
17.4b.2 Off-site disposal: Enviro	"		7.78	12.14	"	

APPENDIX TABLE 3-2 (CONT.)
COST COMPONENT COMPARISON*:
NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES
(7,000 KG/HR)

COST COMPONENT**	NAC/NAG/NAX (ALPHA)		VITRIFICATION		GROUTING	
	LOW	HIGH	NON- ALPHA	ALPHA	NON- ALPHA	ALPHA
(\$000 unless otherwise noted)						
TOTAL LIFE-CYCLE COSTS (CONT.)						
17.0 \$/liter aqueous waste treated over 20 years (Cont.)						
17.5 Grouting (Cont.)						
17.5a On-site disposal						
17.5a.1 Eng. disposal	Not applicable		Not applicable		6.51	6.85
17.5a.2 Shallow land	"		"		3.69	4.02
17.5b Off-site disposal: Envirocare	"		"		3.64	3.98
18.0 \$/mole NO ₃ removed over 20 years (KEI life-cycle cost/2.6 bil. gmols)						
18.1 NAC						
18.1a On-site disposal						
18.1a.1 Engineered disposal	1.11	1.27	Not applicable		Not applicable	
18.1a.2 Shallow-land disposal	0.71	0.87	"		"	
18.1b Off-site disposal: Envirocare	0.58	0.74	"		"	
18.2 NAG						
18.2a On-site disposal						
18.2a.1 Engineered disposal	1.92	2.08	Not applicable		Not applicable	
18.2a.2 Shallow-land disposal	1.41	1.57	"		"	
18.2b Off-site disposal: Envirocare	1.32	1.48	"		"	
18.3 NAX						
18.3a On-site disposal						
18.3a.1 Engineered disposal	1.72	1.73	Not applicable		Not applicable	
18.3a.2 Shallow-land disposal	1.10	1.26	"		"	
18.3b Off-site disposal: Envirocare	1.06	1.22	"		"	
18.4 Vitrification						
18.4a \$1000/ton NO _x						
18.4a.1 On-site disposal						
Engineered disposal	Not applicable		2.16	3.16	Not applicable	
Shallow-land disposal	"		1.65	2.65	"	
18.4a.2 Off-site disposal: Enviro.	"		1.55	2.56	"	
18.4b \$6000/ton NO _x						
18.4b.1 On-site disposal						
Engineered disposal	Not applicable		2.40	3.40	Not applicable	
Shallow-land disposal	"		1.89	2.89	"	
18.4b.2 Off-site disposal: Enviro.	"		1.80	2.80	"	
18.5 Grouting						
18.5a On-site disposal						
18.5a.1 Eng. disposal	Not applicable		Not applicable		1.50	1.58
18.5a.2 Shallow land	"		"		0.85	0.93
18.5b Off-site disposal: Envirocare	"		"		0.83	0.91

APPENDIX TABLE 3-2 (CONT.) **COST COMPONENT COMPARISON*:** **NAC, NAG, NAX, VITRIFICATION, AND GROUTING FACILITIES** **(7,000 KG/HR)**

* The low estimate is KEI's estimate based on EG&G data and/or data from the MMES cost estimate while the high estimate is an average of vitrification and grouting data.

The vitrification and grouting analyses are extrapolations of EG&G cost data published in *Waste Management Facilities Cost Information for Mixed Low-Level Waste* (Fred Feizollahi and David Shropshire, Idaho National Engineering Laboratory, EGG-WM-10962, March 1994).

The use of data from two different sources creates a problem when trying to make a direct comparison of the data. KEI made every attempt to place the data on the same basis, but please note that discrepancies may exist. [Note: It may be desirable to have the EG&G/Morrison Knudsen team that performed the vitrification and grouting analyses perform such an analysis on the NAC/NAG/NAX process.

** In the numbering sequence throughout this table, an a, b, c, etc. indicates an option. For example, 11.0a and 11.0b indicate two different options. However, 9.1 is comprised of the sum of 9.1.1, 9.1.2, etc. One exception for this is in the numbering sequences for NAC/NAG/NAX. For example, 12.0 is not comprised of the sum of 12.1, 12.2, and 12.3.

- 1 Includes ammonia-handling off-gas system and calcining equipment to make ceramic clinker.
- 2 Assumed NAC/NAG/NAX will consume 330 million lbs. of aluminum over 20 years (\$0.40/lb.).
- 3 Industry sources indicate that the economics of ammonia recovery are not good enough to justify reclaiming it.
- 4 EG&G life-cycle cost = 1.0 + 2.0 + 3.0 + 4.0 + 5.6 + 6.0 = 7.0.
- 5 For comparison, the EG&G life-cycle cost for vitrification of remote handled TRU waste (the worst-case scenario) is \$17.5 billion (\$29/L, \$110/gal). This results in a KEI life-cycle cost range of \$30-35/L (\$127-148/gal). This estimate is based on an extrapolation of data obtained from *Waste Management Facilities Cost Information for Transuranic Waste* (Fred Feizollahi and David Shropshire, Idaho National Engineering Laboratory, EGG-WM-11274, June 1994).

REMOTE-HANDLED TRU WASTE

	\$1,000/TON NO _x TREATED			\$6,000/TON NO _x TREATED		
	\$ (000)	\$/L	\$/gal	\$ (000)	\$/L	\$/gal
On-site						
Engineered disposal	20,354,256	34	144	20,980,985	35	148
Shallow-land disposal	19,029,171	32	135	19,655,900	33	140
Off-site						
NTS	17,797,683	30	127	18,424,412	31	131
Envirocare	18,790,450	31	131	19,417,179	32	135

Also for comparison, John Plodinec estimates the following for vitrification and grouting of Savannah River's HLW:

Tank farm cost, transfer from storage to treatment (not included in KEI's analysis):	\$17.18/L
HLW vitrification (KEI assumes that this is comparable to EG&G life-cycle cost):	16.60/L
Saltstone treatment (KEI assumes that this is comparable to EG&G life-cycle cost):	0.80/L

The following compares cost components from KEI's vitrification estimate with figures obtained from Bob Watrous and Kale Boomer of Hanford:

VITRIFICATION

Cost Component	Hanford (Fluor)	KEI
R&D	\$280 mil.	-----
Startup	84 mil.	-----
Studies and bench-scale test costs	-----	108 mil.
Demonstration costs	-----	163 mil.
Operations budget funded activities	-----	699 mil.
Capital equipment	1.35 bil. ^a	1.04 bil.
Operating & maintenance	1-2 bil.	3.3 bil.
D&D	84 mil. ^b	94 mil.
Equipment disposal	405 mil. ^c	-----
Off-gas treatment	^d	125-752 mil.
TOTAL \$	3.2-4.2 bil.	5.5-6.2 bil.
\$/gmole Na	0.91-1.20	2.13-2.37

APPENDIX TABLE 3-2 (CONT.) **COST COMPONENT COMPARISON*:** **NAC/NAG/NAX, VITRIFICATION, AND GROUTING FACILITIES** **(7,000 KG/HR)**

Fluor assumed 60% operating efficiency, 13 years of operation and 360 million liters total volume (28 million L/year) having 3.5 billion gmoles Na (9.7 M). Fluor assumed the waste would undergo pretreatment to remove cesium and to reduce the volume, which would increase the concentration from almost 5 M to almost 10 M. The final glass product will have <100 nCi alpha/g. KEI assumed 60% operating efficiency, 20 years of operation, and 600 million liters having 2.6 billion gmoles Na (4.3 M).

^a Assumed the same as for HLW because the only difference is 3-foot wall thickness for LLW versus 5-foot for HLW.

Includes pretreatment costs and off-gas treatment.

^b \$28 mil./year for 3 years.

^c 30% of capital.

^d Included in capital equipment.

- ⁶ Assumes final-waste-treatment components are housed in the building costed in section 3.0 of this table. Grouting component costs are based on Six-Tenths Rule calculations using 1,818 kg/hr component costs as the known costs. Vittrification component costs are based on X-Tenths Rule calculations using 455 kg/hr component costs and X/10ths values based on Savannah River vittrification budget figures (refer to Appendix Table 4-7).
- ⁷ According to industry sources, the treatment cost per ton of NO_x could range from \$1,000-6,000/ton NO_x, assuming the off-gas is not radioactive. Because the price for NO_x treatment has dropped significantly over the last few years, the actual cost could be towards the lower end of the range. KEI assumed a rate of 1,084 kg NO_x/hr x 5,256 hr/yr x 20 yr = 113,950,080 kg (250,690,176 lb) NO_x/20 years.
- ⁸ KEI assumed that non-alpha material contains traces of radioactivity, which costs the same to ship as alpha material. Transportation costs via flat-bed truck (46,000 lb. max./single stacking can hold 14 B-25 containers (90 ft³ each)/double stacking can hold 28) are based on the following quote from Kendrick Trucking of Harriman, TN:
Hanford to Envirocare:	\$1633 per load	Oak Ridge to Envirocare:	\$3822 per load
Hanford to Nevada:	\$2470 per load	Oak Ridge to Nevada:	\$4006 per load
- Single stack: 1260 ft³, 35.7 m³
Double stack: 2520 ft³, 71.4 m³
- ⁹ Disposal fees are difficult to obtain. The Nevada Test Site (NTS) cost was obtained from the site manager, Bruce Becker of Reynolds Electrical and Engineering Co., and are considered to be reliable. He also provided the estimates for Hanford and Barnwell. Envirocare costs were provided by Rick Korynta of DOE (ORO).
- ¹⁰ The low value for disposal at the NTS is misleading. Such a low fee cannot be based on all of the life-cycle costs included by KEI in its analysis. Because NTS is a DOE facility, its life-cycle costs should be comparable to the on-site values presented in this table.
- ¹¹ The estimated volume of NAC waste to be disposed over 20 years is 358,648 m³ (12,663,260 ft³). The volume of waste is expected to be the same for vittrification and NAG, 536,921 m³ (18,957,780 ft³). The estimated volume of NAX waste (grouted calcine) is 753,500 m³ (26,590,320 ft³). The estimated volume of grouted material is 840,000 m³ (29,664,142 ft³). Refer to p.126 for a discussion of how these figures were obtained.
- ¹² \$/ft³ = (13.x + 14.x)\volume to be disposed in ft³ (see Note 11 above).

Source: KEI

GROUTING

Appendix Table 3-3 provides an analysis of the 1,818 kg/hr non-alpha grouting facility costs. Appendix Table 3-4 provides this information for an alpha facility. Appendix Table 3-5 provides a detailed listing of the equipment and installation costs for a non-alpha grouting facility. These costs are for the largest facility that MK analyzed. Appendix Table 3-6 provides the data for an alpha facility. Table 3-7 provides an analysis of the total equipment and installation costs for the non-alpha and alpha grouting facilities. Table 3-8 presents the building cost assumptions used by the WMFCI team in their large-facility grouting analysis. Tables 3-9 and 3-10 present KEF's estimate for a 7,000 kg/hr facility.

**APPENDIX TABLE 3-3
GROUTING COST COMPONENTS:
1,818 KG/HR INPUT CAPACITY LLW/MLLW FACILITY
(NON-ALPHA)**

COST COMPONENT	FACILITY COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT OF COST COMPONENT
1.0 Studies and bench-scale test costs	0	0	0
1.1 Manpower costs during research	0	0	0
1.2 Equipment costs	0	0	0
1.3 Installation costs	0	0	0
1.4 Project management before Title I	0	0	0
1.5 Contingency	0	0	0
2.0 Demonstration costs	0	0	0
2.1 Manpower costs during demonstration	0	0	0
2.2 Design cost	0	0	0
2.3 Inspection cost	0	0	0
2.4 Project management	0	0	0
2.5 Construction cost	0	0	0
2.5.1 Building structure cost	0	0	0
2.5.2 Equipment costs	0	0	0
2.5.3 Indirect	0	0	0
2.6 Construction management costs	0	0	0
2.7 Management reserve	0	0	0
2.8 Contingency	0	0	0
3.0 Production facility construction costs	37,692	23.03	100
3.1 Design cost	2,348	1.43	6.23
3.2 Inspection cost	1,370	0.84	3.63
3.3 Project management	1,957	1.20	5.19
3.4 Construction cost	19,567	11.96	51.9
3.4.1 Building structure costs	6,709	4.10	17.8
3.4.2 Equipment costs	8,459	5.17	22.4
3.4.3 Indirect	4,399	2.69	11.7
3.5 Construction management	3,346	2.04	8.88
3.6 Management reserve	1,957	1.20	5.19
3.7 Contingency	7,147	4.37	19.0

APPENDIX TABLE 3-3 (CONT.)
GROUTING COST COMPONENTS:
1,818 KG/HR INPUT CAPACITY LLW/MLLW FACILITY
(NON-ALPHA)

COST COMPONENT	FACILITY COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT OF COST COMPONENT
4.0 Operations budget funded activities	7,315	4.47	100
4.1 Conceptual design	565	0.345	7.72
4.2 Safety assurance	377	0.23	5.15
4.3 NEPA permitting (location operating cost)	0	0	0
4.4 Preparation for operations	5,708	3.49	78.0
4.5 Project management	665	0.41	9.09
5.0 Operating and maintenance costs			
5.1 Annual operating costs	1,568	0.96	27.5
5.2 Annual utility costs	50	0.031	0.876
5.3 Annual material costs	2,258	1.38	39.6
5.4 Annual maintenance costs	690	0.42	12.1
5.5 Contingency	1,142	0.70	20.0
Subtotal	5,708	3.49	100
Total 20-year O&M cost (20 times 5.0)	114,160	69.75	---
6.0 Decontamination & decommissioning	4,499	2.75	100
7.0 Pre-operations (1.0 + 2.0 + 4.0)	7,315	4.47	100
8.0 EG&G 20-year life-cycle cost estimate (3.0 + 5.0 + 6.0 + 7.0)	163,666	100.0	100

* Input capacity: 4,000 lb/hr (1,818 kg/hr)

Source: Based on information obtained by KEI from MK-Environmental

TABLE 3-4
GROUTING COST COMPONENTS:
1,818 KG/HR INPUT CAPACITY LLW/MLLW FACILITY (ALPHA)

COST COMPONENT	FACILITY COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT OF COST COMPONENT
1.0 Studies and bench-scale test costs	0	0	0
1.1 Manpower costs during research	0	0	0
1.2 Equipment costs	0	0	0
1.3 Installation costs	0	0	0
1.4 Project management before Title I	0	0	0
1.5 Contingency	0	0	0
2.0 Demonstration costs	0	0	0
2.1 Manpower costs during demonstration	0	0	0
2.2 Design cost	0	0	0
2.3 Inspection cost	0	0	0
2.4 Project management	0	0	0
2.5 Construction cost	0	0	0
2.5.1 Building structure cost	0	0	0
2.5.2 Equipment costs	0	0	0
2.5.3 Indirect	0	0	0
2.6 Construction management costs	0	0	0
2.7 Management reserve	0	0	0
2.8 Contingency	0	0	0
3.0 Production facility construction costs	80,208	32.19	100
3.1 Design cost	4,997	2.01	6.23
3.2 Inspection cost	2,915	1.17	3.63
3.3 Project management	4,164	1.67	5.19
3.4 Construction cost	4,162	16.7	51.9
3.4.1 Building structure costs	13,722	5.51	17.1
3.4.2 Equipment costs	18,536	7.45	23.1
3.4.3 Indirect	9,361	3.76	11.7
3.5 Construction management	7,120	2.86	8.88
3.6 Management reserve	4,164	1.67	5.19
3.7 Contingency	15,209	6.10	19.0
4.0 Operations budget funded activities	10,586	4.25	100
4.1 Conceptual design	1,203	0.48	11.4
4.2 Safety assurance	802	0.32	7.58
4.3 NEPA permitting (location operating cost)	0	0	0
4.4 Preparation for operations	7,619	3.06	72.0
4.5 Project management	962	3.86	9.09

TABLE 3-4 (CONT.)
GROUTING COST COMPONENTS:
1,818 KG/HR INPUT CAPACITY LLW/MLLW FACILITY (ALPHA)

COST COMPONENT	FACILITY COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT OF COST COMPONENT
5.0 Operating and maintenance costs			
5.1 Annual operating costs	2,268	0.91	29.8
5.2 Annual utility costs	52	0.021	0.683
5.3 Annual material costs	2,258	0.91	29.6
5.4 Annual maintenance costs	1,517	0.61	19.9
5.5 Contingency	1,524	0.61	20.0
Subtotal	7,619	3.06	100
Total 20-year O&M cost (20 times 5.0)	152,380	61.16	----
6.0 Decontamination & decommissioning	5,967	2.40	100
7.0 Pre-operations (1.0 + 2.0 + 4.0)	10,586	4.25	100
8.0 EG&G 20-year life-cycle cost estimate (3.0 + 5.0 + 6.0 + 7.0)	249,141	100	100

Source: Based on information obtained by KEI from MK-Environmental

APPENDIX TABLE 3-5
DETAILED LISTING OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost (\$000)	Amt. (\$000)	Unit Cost (\$000)	Amt. (\$000)	Total Unit Oper. (\$000)
1.0 Prepare and Feed Incoming Waste			2328		583	2911
Bin hoist/pusher	1	66	66	8	8	74
Disch. & oversize load hopper (100 CF)	1	60	60	8	8	68
Primary shredder (.25, 1.5, 2 TPH)	1	528	528	106	106	634
Secondary shredder (.5, 1.5, 3 TPH)	1	220	220	44	44	264
Tertiary shredder (1,2,4 TPH)	1	132	132	26	26	158
Live bottom bulk storage	1	60	60	8	8	68
Conveyor/canister handler	1	80	80	10	10	90
Manipulation crane—5 ton	1	220	220	20	20	240
Dust collection system w/blower	Lot	108	108	17	17	125
HEPA filter	4	25	100	5	20	120
Allowance for piping/mechanical	Lot	472	472	160	160	632
Allowance for electrical/control	Lot	236	236	134	134	370
Calibration, testing & startup	Lot	46	46	22	22	68
2.0 Store & feed binder			852		180	853
Pneumatic feed						
Binder storage silo						
Silo discharge feeder						
Mixing station						
Binder feed pump						
Complete package per above detail	2	250	500	40	80	580
Conveyor	16	6	96	1	16	112
Allowance for piping/mechanical	Lot	150	150	29	29	179
Allowance for electrical/control	Lot	89	89	48	48	137
Calibration, testing & startup	Lot	17	17	7	7	24
3.0 Micro-solidification			1479		332	1811
Conveyor—Roller (24" x 15')						
Binder feed prep						
Binder feed hopper						
Waste feed prep						
Binder/waste mixing station						
Drum tumbler						
Weigh station						
Drum capping & cap removal						

APPENDIX TABLE 3-5 (CONT.)
DETAILED LISTING OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost (\$000)	Amt. (\$000)	Unit Cost (\$000)	Amt. (\$000)	Total Unit Oper. (\$000)
3.0 Micro-solidification (Cont.)						
Dust collection & ventilation						
Allowance for structural steel—TN						
Complete package per above detail	4	250	1000	38	152	1152
Allowance for piping/mechanical	Lot	300	300	91	91	391
Allowance for electrical/control	Lot	150	150	76	76	226
Calibration, testing & startup	Lot	29	29	13	13	42
4.0 Macro-solidification						
Included in GL-3						
5.0 Drum capping & washing			716		262	978
Drum wash/cap unit	4	70	280	15	60	340
Flush water collection & conveying	2	30	60	18	36	96
Conveyor	24	6	144	1	24	168
Allowance for piping/mechanical	Lot	145	145	72	72	217
Allowance for electrical/control	Lot	73	73	60	60	133
Calibration, testing & startup	Lot	14	14	10	10	24
6.0 Electrical distribution & MCC			272		125	397
Main control panel	11	10	110	2	22	132
Motor control center	80	1.5	120	0.5	40	160
Allowance for piping/mechanical	Lot	2	2	19	19	21
Allowance for electrical/control	Lot	35	35	37	37	72
Calibration, testing & startup	Lot	5	5	7	7	12
7.0 Utilities & mechanical			334		188	522
Sump pump	3	5	15	2	6	21
Standby emergency power system	Lot	210	210	80	80	290
Allowance for piping/mechanical	Lot	68	68	52	52	120
Allowance for electrical/control	Lot	34	34	43	43	77
Calibration, testing & startup	Lot	7	7	7	7	14
8.0 Heating, ventilation & exhaust						
Included in building cost						

APPENDIX TABLE 3-5 (CONT.)
DETAILED LISTING OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost (\$000)	Amt. (\$000)	Unit Cost (\$000)	Amt. (\$000)	Total Unit Oper. (\$000)
9.0 Radiation monitoring equipment			204		94	298
Area monitors	18	4	72	1.5	27	99
Air monitors	10	10	100	2	20	120
Allowance for piping/mechanical	Lot	2	2	14	14	16
Allowance for electrical/control	Lot	26	26	28	28	54
Calibration, testing & startup	Lot	4	4	5	5	9
10.0 Other equipment			407		103	510
Fire suppression system (shredder area)	4	30	120	5	20	140
Fire suppression system (other area area)	4	30	120	5	20	140
Emergency shower & decon station	Lot	35	35	7	7	42
Allowance for piping/mechanical	Lot	83	83	28	28	111
Allowance for electrical/control	Lot	41	41	24	24	65
Calibration, testing & startup	Lot	8	8	4	4	12
TOTAL						26836

Source: Chuck Biagi, Morrison Knudsen Corp.

APPENDIX TABLE 3-6
DETAILED LISTING OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR, ALPHA)

Description	Materials & Equip.			Installation		Cost Total Unit Oper.
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	
1.0 Prepare and feed incoming waste			6175		1928	8103
Bin hoist/pusher	1	99	99	8	8	107
Disch. & oversize load hopper (100 CF)	1	60	60	8	8	68
Primary shredder (.25, 1.5, 2 TPH)	1	792	792	158	158	950
Secondary shredder (.5, 1.5, 3 TPH)	1	320	320	64	64	384
Tertiary shredder (1,2,4 TPH)	1	208	208	42	42	250
Live bottom bulk storage	1	60	60	8	8	68
Conveyor/canister handler	1	120	120	10	10	130
Manipulation crane	1	450	450	60	60	510
Dust collection system w/blower	Lot	162	162	17	17	179
HEPA filter	4	25	150	5	20	170
Shield windows	1	130	130	44	44	174
CCTV	3	10	30	2	6	36
Airlock	3	124	372	39	117	489
Allowance for piping/mechanical	3	886	2656	337	1011	3667
Allowance for electrical/control	Lot	443	443	281	281	724
Calibration, testing & startup	Lot	121	121	74	74	195
2.0 Store & feed binder			953		210	1163
Pneumatic feed						
Binder storage silo & discharge feeder						
Mixing station						
Binder feed pump						
Complete package per above detail	2	250	500	40	80	580
Conveyor	16	9	144	1	16	160
Allowance for piping/mechanical	Lot	193	193	58	58	251
Allowance for electrical/control	Lot	97	97	48	48	145
Calibration, testing & startup	Lot	19	19	8	8	27
3.0 Micro-solidification			3730		846	4576
Conveyor—Roller (24" x 15')						
Binder feed prep & hopper						
Waste feed prep						
Binder/waste mixing station & drum tumbler						
Weigh station						
Drum capping & cap removal						
Dust collection & ventilation						
Allowance for structural steel—TN						
Complete package per above detail	4	375	1500	38	152	1652

APPENDIX TABLE 3-6(CONT.)
DETAILED LISTING OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR, ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
3.0 Micro-solidification (Cont.)						
Manipulation crane	1	450	450	60	60	510
Shield window	1	130	130	44	44	174
CCTV	7	10	70	2	14	84
Airlock	3	124	372	39	117	489
Allowance for piping/mechanical	Lot	757	757	232	232	989
Allowance for electrical/control	Lot	378	378	194	194	572
Calibration, testing & startup	Lot	73	73	33	33	106
4.0 Macro-solidification						
Included in GL-3						
5.0 Drum capping & washing						
			2106		633	2739
Drum wash/cap unit	4	70	280	15	60	340
Flush water collection & conveying	2	30	60	18	36	96
Conveyor	24	9	216	1	24	240
Manipulation crane	1	450	450	40	40	490
Shield window	1	130	130	44	44	174
CCTV	4	10	40	2	8	48
Airlock	2	124	248	39	78	326
Allowance for piping/mechanical	Lot	427	427	174	174	601
Allowance for electrical/control	Lot	214	214	145	145	359
Calibration, testing & startup	Lot	41	41	24	24	65
6.0 Electrical distribution & MCC						
			275		127	402
Main control panel	11	10	110	2	22	132
Motor control center	82	1.5	123	0.5	41	164
Allowance for piping/mechanical	Lot	2	2	19	19	21
Allowance for electrical/control	Lot	35	35	38	38	73
Calibration, testing & startup	Lot	5	5	7	7	12
7.0 Utilities & mechanical						
			334		188	522
Sump pump	3	5	15	2	6	21
Standby emergency power system	Lot	210	210	80	80	290
Allowance for piping/mechanical	Lot	68	68	52	52	120
Allowance for electrical/control	Lot	34	34	43	43	77
Calibration, testing & startup	Lot	7	7	7	7	14
8.0 Heating, ventilation & exhaust						
Included in building cost						

APPENDIX TABLE 3-6 (CONT.)
DETAILED LISTING OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR, ALPHA)

Description	Materials & Equip.			Installation		Cost
	Qty.	Unit	Amt., \$000	Unit	Amt., \$000	Total Unit Oper.
9.0 Radiation monitoring equipment			259		78	337
Area monitors	14	6	84	1.5	21	105
Air monitors	9	15	135	2	18	153
Allowance for piping/mechanical	Lot	2	2	12	12	14
Allowance for electrical/control	Lot	33	33	23	23	56
Calibration, testing & startup	Lot	5	5	4	4	9
10.0 Other equipment			611		103	714
Fire suppression system (shredder area)	4	45	180	5	20	200
Fire suppression system (other area)	4	45	180	5	20	200
Emergency shower & decon station	Lot	35	53	7	7	60
Allowance for piping/mechanical	Lot	124	124	28	28	152
Allowance for electrical/control	Lot	62	62	24	24	86
Calibration, testing & startup	Lot	12	12	4	4	16
TOTAL						18104

Source: Chuck Biagi, Morrison Knudsen Corp.

APPENDIX TABLE 3-7
ANALYSIS OF TOTAL EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
1.0 Prepare and feed incoming waste	2911	35.2	100	8103	43.7	100
Bin hoist/pusher	74			107		
Disch. & oversize load hopper (100 CF)	68			68		
Primary shredder (.25, 1.5, 2 TPH)	634			950		
Secondary shredder (.5, 1.5, 3 TPH)	264			384		
Tertiary shredder (1,2,4 TPH)	158			250		
Live bottom bulk storage	68			68		
Conveyor/canister handler	90			130		
Manipulation crane—5 ton	240			510		
Dust collection system w/blower	125			179		
HEPA filter	120			170		
Allowance for piping/mechanical	632		21.7	3669		45.3
Allowance for electrical/control	370		12.7	724		8.93
Calibration, testing & startup	68		2.34	195		2.41
Shield windows	0		0	174		2.15
CCTV	0		0	36		0.444
Airlock	0		0	489		6.03
2.0 Store & feed binder	853	10.3	100	1163	6.27	100
Pneumatic feed						
Binder storage silo						
Silo discharge feeder						
Mixing station						
Binder feed pump						
Complete package per above detail	580			580		
Conveyor	112			160		
Allowance for piping/mechanical	179		21.0	251		21.6
Allowance for electrical/control	137		16.1	145		12.5
Calibration, testing & startup	24		2.81	27		2.32
3.0 Micro-solidification	1811	21.9	100	4576	24.7	100
Conveyor—Roller (24" x 15')						
Binder feed prep						
Binder feed hopper						
Waste feed prep						
Binder/waste mixing station						
Drum tumbler						
Weigh station						
Drum capping & cap removal						

APPENDIX TABLE 3-7 (CONT.)
ANALYSIS OF TOTAL EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
3.0 Micro-solidification (Cont.)						
Dust collection & ventilation						
Allowance for structural steel—TN						
Complete package per above detail	1152			1652		36.1
Allowance for piping/mechanical	391		21.6	989		21.6
Allowance for electrical/control	226		12.5	572		12.5
Calibration, testing & startup	42		2.32	106		2.32
Manipulation crane	0		0	510		11.1
Shield window	0		0	174		3.80
CCTV	0		0	84		1.84
Airlock	0		0	489		10.7
4.0 Macro-solidification						
Included in GL-3						
5.0 Drum capping & washing	978	11.8	100	2739	14.8	100
Drum wash/cap unit	340			340		
Flush water collection & conveying	96			96		
Conveyor	168			240		
Allowance for piping/mechanical	217		22.2	601		
Allowance for electrical/control	133		13.6	359		
Calibration, testing & startup	24		2.45	65		
Manipulation crane	0		0	490		17.9
Shield window	0		0	174		6.35
CCTV	0		0	48		1.75
Airlock	0		0	326		11.9
6.0 Electrical distribution & MCC	397	4.79	100	402	2.17	100
Main control panel	132			132		
Motor control center	160			164		
Allowance for piping/mechanical	21			21		
Allowance for electrical/control	72			73		
Calibration, testing & startup	12			12		
7.0 Utilities & mechanical	522	6.30	100	522	2.81	100
Sump pump	21			21		
Standby emergency power system	290			290		
Allowance for piping/mechanical	120			120		
Allowance for electrical/control	77			77		
Calibration, testing & startup	14			14		

APPENDIX TABLE 3-7 (CONT.)
ANALYSIS OF TOTAL EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW GROUT FACILITY (1,818 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
8.0 Heating, ventilation & exhaust Included in building cost						
9.0 Radiation monitoring equipment	298	3.60	100	337	1.82	100
Area monitors	99			105		
Air monitors	120			153		
Allowance for piping/mechanical	16			14		
Allowance for electrical/control	54			56		
Calibration, testing & startup	9			9		
10.0 Other equipment	510	6.16	100	714	3.85	100
Fire suppression system (shredder area)	140			200		
Fire suppression system (other area area)	140			200		
Emergency shower & decon station	42			60		
Allowance for piping/mechanical	111			152		
Allowance for electrical/control	65			86		
Calibration, testing & startup	12			16		
TOTAL	8280	100	100	18556	100	100

Source: Chuck Biagi, Morrison Knudsen-Environmental Corp.

APPENDIX TABLE 3-8
GROUT BUILDING COST/AREA SUMMARY (1,818 KG/HR)

UNIT OPERATION	BUILDING AREA, FT ²				TOTAL COST, \$
	ADMIN	MED. HAZ.	MAINT	ALPHA	
NON-ALPHA					
Prepare and feed incoming waste		300	1400		1278
Store & feed binder		173	828		735
Micro-solidification		574	2752		2443
Macro-solidification					
Drum capping and washing		329	1580		1402
Electrical distribution & MCC		616			259
Utilities & mechanical		616			259
Heating, ventilation & exhaust		792			333
Radiation monitoring equipment					
Other equipment					
TOTAL		3400	6600		6709
PER CENT		34	66		
ALPHA					
Prepare and feed incoming waste		257	550	1232	2616
Store & feed binder		1213			509
Micro-solidification		587	1259	2818	5984
Macro-solidification					---
Drum capping and washing		345	741	1658	3521
Electrical distribution & MCC		812			341
Utilities & mechanical		812			341
Heating, ventilation & exhaust		975			410
Radiation monitoring equipment					
Other equipment					
TOTAL		5001	2550	5708	13722
PER CENT		38	19	43	

Source: Chuck Biagi and Belinda Wong, Morrison Knudsen

APPENDIX TABLE 3-9
EG&G GROUTING COST COMPONENTS:
7,000 KG/HR INPUT CAPACITY LLW/MLLW FACILITY
(NON-ALPHA)

COST COMPONENT*	COST (\$000)	% EG&G LIFE CYCLE	PER CENT COST CATEGORY
1.0 Studies and bench-scale test costs	0	0	0
1.1 Manpower costs during research	0	0	0
1.2 Equipment costs	0	0	0
1.3 Installation costs	0	0	0
1.4 Project management before Title I	0	0	0
1.5 Contingency	0	0	0
2.0 Demonstration costs	0	0	0
2.1 Manpower costs during demonstration	0	0	0
2.2 Design cost	0	0	0
2.3 Inspection cost	0	0	0
2.4 Project management	0	0	0
2.5 Construction cost	0	0	0
2.5.1 Building structure cost	0	0	0
2.5.2 Equipment costs	0	0	0
2.5.3 Indirect	0	0	0
2.6 Construction management costs	0	0	0
2.7 Management reserve	0	0	0
2.8 Contingency	0	0	0
3.0 Production facility construction costs**	86,403,143	23.5	100
3.1 Design cost	5,382,430	1.46	6.23
3.2 Inspection cost	3,140,515	0.85	3.63
3.3 Project management	4,486,123	1.22	5.19
3.4 Construction cost	44,854,354	12.2	51.9
3.4.1 Building structure costs	15,379,356	4.17	17.8
3.4.2 Equipment costs	19,390,963	5.26	22.4
3.4.3 Indirect	10,084,035	2.74	11.7
3.5 Construction management	7,670,193	2.08	8.88
3.6 Management reserve	4,486,123	1.22	5.19
3.7 Contingency	1,638,404	4.44	19.0
4.0 Operations budget funded activities (100% of 7.0)	16,532,000	4.49	100
4.1 Conceptual design	1,276,270	0.35	7.72
4.2 Safety assurance	851,398	0.23	5.15
4.3 NEPA permitting (location operating cost)	0	0	0
4.4 Preparation for operations	12,894,960	3.50	78.0
4.5 Project management	1,502,759	0.41	9.09

APPENDIX TABLE 3-9 (CONT.)
EG&G GROUTING COST COMPONENTS:
7,000 KG/HR INPUT CAPACITY LLW/MLLW FACILITY
(NON-ALPHA)

COST COMPONENT*	COST (\$000)	% EG&G LIFE CYCLE	PER CENT COST CATEGORY
5.0 Operating and maintenance costs**			
5.1 Annual operating costs	3,509,256	0.95	27.5
5.2 Annual utility costs	111,902	0.03	0.878
5.3 Annual material costs	5,053,508	1.37	39.7
5.4 Annual maintenance costs	1,544,252	0.42	12.1
5.5 Contingency	2,555,849	0.69	20.0
5.6 Subtotal	12,774,767	----	100
5.7 Total 20-year O&M cost (20 times 5.6)	255,495,342	69.3	----
6.0 Decontamination & decommissioning**	10,015,067	2.72	100
7.0 Pre-operations (1.0 + 2.0 + 4.0)**	16,532,000	4.49	100
7.0 EG&G 20-year Life-cycle Cost Est. (3.0 + 5.7 + 6.0 + 7.0) **	368,445,804	100	100

* Percentages based on EG&G grouting data (non-alpha) at 1,818 kg/hr unless otherwise noted.

** 6/10ths Rule extrapolation.

Source: Based on information obtained by KEI from MK-Environmental

APPENDIX TABLE 3-10
EG&G GROUTING COST COMPONENTS:
7,000 KG/HR INPUT CAPACITY LLW/MLLW FACILITY (ALPHA)

COST COMPONENT*	COST (\$000)	% EG&G LIFE CYCLE	PER CENT COST CATEGORY
1.0 Studies and bench-scale test costs	0	0	0
1.1 Manpower costs during research	0	0	0
1.2 Equipment costs	0	0	0
1.3 Installation costs	0	0	0
1.4 Project management before Title I	0	0	0
1.5 Contingency	0	0	0
2.0 Demonstration costs	0	0	0
2.1 Manpower costs during demonstration	0	0	0
2.2 Design cost	0	0	0
2.3 Inspection cost	0	0	0
2.4 Project management	0	0	0
2.5 Construction cost	0	0	0
2.5.1 Building structure cost	0	0	0
2.5.2 Equipment costs	0	0	0
2.5.3 Indirect	0	0	0
2.6 Construction management costs	0	0	0
2.7 Management reserve	0	0	0
2.8 Contingency	0	0	0
3.0 Production facility construction costs**	182,785,492	32.2	100
3.1 Design cost	11,387,631	2.01	6.23
3.2 Inspection cost	6,642,975	1.17	3.63
3.3 Project management	9,489,313	1.67	5.19
3.4 Construction cost	94,845,270	16.7	51.9
3.4.1 Building structure costs	31,270,977	5.52	17.1
3.4.2 Equipment costs	42,241,570	7.45	23.1
3.4.3 Indirect	21,332,722	3.76	11.7
3.5 Construction management	16,225,722	2.86	8.88
3.6 Management reserve	9,489,313	1.67	5.19
3.7 Contingency	34,659,692	6.11	19.0
4.0 Operations budget funded activities (100% of 7.0)	24,160,000	4.26	100
4.1 Conceptual design	2,754,240	0.48	11.4
4.2 Safety assurance	1,831,328	0.32	7.58
4.3 NEPA permitting (location operating cost)	0	0	0
4.4 Preparation for operations	17,395,200	3.07	72.0
4.5 Project management	2,196,144	0.39	9.09

APPENDIX TABLE 3-10 (CONT.)
EG&G GROUTING COST COMPONENTS:
7,000 KG/HR INPUT CAPACITY LLW/MLLW FACILITY (ALPHA)

COST COMPONENT*	COST (\$000)	% EG&G LIFE CYCLE	PER CENT COST CATEGORY
5.0 Operating and maintenance costs**			
5.1 Annual operating costs	5,155,769	0.91	29.8
5.2 Annual utility costs	118,210	0.02	0.683
5.3 Annual material costs	5,133,037	0.91	29.6
5.4 Annual maintenance costs	3,448,546	0.61	19.9
5.5 Contingency	3,464,459	0.61	20.0
5.6 Subtotal	17,320,021	----	100
5.7 Total 20-year O&M cost (20 times 5.6)	346,400,416	61.1	---
6.0 Decontamination & decommissioning**	13,552,703	2.39	100
7.0 Pre-operations**	24,160,000	4.26	100
8.0 EG&G 20-year life-cycle cost estimate (4.0 + 5.7 + 6.0 + 7.0)**	566,898,174	100	100

* Percentages based on EG&G grouting data (alpha) at 1,818 kg/hr unless otherwise noted.

** 6/10ths Rule extrapolation.

Source: Based on information obtained by KEI from MK-Environmental

VITRIFICATION

Appendix Table 3-11 provides an analysis of the 455 kg/hr non-alpha vitrification facility costs. Appendix Table 3-12 provides this information for an alpha facility. Appendix Table 3-13 provides a detailed listing of the equipment and installation costs for a 455 kg/hr non-alpha vitrification facility. These costs are for the largest facility that MK analyzed. Appendix Table 3-14 provides the data for an alpha facility. Table 3-15 provides an analysis of the total equipment and installation costs for the non-alpha and alpha grouting facilities. Table 3-16 is an analysis of the total installed costs. Table 3-17 presents the building cost assumptions used by the WMFCI team in their large-facility grouting analysis. Table 3-18 presents KEI's estimate for a 7,000 kg/hr facility.

**APPENDIX TABLE 3-11
VITRIFICATION COST COMPONENTS:
LLW/MLLW FACILITY (455 KG/HR, NON-ALPHA)**

COST COMPONENT	COMPONENT COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT COST COMPONENT
1.0 Studies and bench-scale test costs	3,163	1.22	100
1.1 Manpower costs during research	1,800	0.69	56.9
1.2 Equipment costs	100	0.04	3.16
1.3 Installation costs	400	0.15	12.6
1.4 Project management before Title I (10% of 1.1 through 1.3)	230	0.09	7.27
1.5 Contingency (25% of 1.1 through 1.4)	633	0.24	20.0
2.0 Demonstration costs	4,769	1.83	100
2.1 Manpower costs during demonstration	2,400	0.92	50.3
2.2 Design cost (30% of 2.5)	244	0.09	5.12
2.3 Inspection cost (7% of 2.5)	57	0.02	1.19
2.4 Project management (10% of 2.5)	81	0.03	1.70
2.5 Construction cost	813	0.31	17.0
2.5.1 Building structure cost	80	0.03	1.68
2.5.2 Equipment costs	550	0.21	11.5
2.5.3 Indirect (29% of 2.5.1 & 2.5.2)	183	0.07	3.84
2.6 Construction management (17% of 2.5)	139	0.05	2.91
2.7 Management reserve (10% of 2.5)	81	0.03	1.70
2.8 Contingency (25% of 2.1 through 2.7)	954	0.37	20.0
3.0 Production facility construction costs	94,063	36.16	100
3.1 Design cost (12% of 3.4)	5,860	2.25	6.23
3.2 Inspection cost (7% of 3.4)	3,418	1.31	3.63
3.3 Project management (10% of 3.4)	4,883	1.88	5.19
3.4 Construction cost	48,833	18.77	51.9
3.4.1 Building structure costs	15,506	5.96	16.5
3.4.2 Equipment costs	22,349	8.59	23.8
3.4.4 Indirect (29% of 3.4.1 & 3.4.2)	10,978	4.22	11.7
3.5 Construction management (17% of 3.4)	8,350	3.21	8.88
3.6 Management reserve (10% of 3.4)	4,883	1.88	5.19
3.7 Contingency (25% of 3.1 through 3.5)	17,836	6.86	19.0

TABLE 3-11 (CONT.)
VITRIFICATION COST COMPONENTS:
LLW/MLLW FACILITY (455 KG/HR, NON-ALPHA)

COST COMPONENT	COMPONENT COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT COST COMPONENT
4.0 Operations budget funded activities	10,142	3.90	100
4.1 Conceptual design (1.5% of 3.0)	1,411	0.54	13.9
4.2 Safety assurance (1% of 3.0)	941	0.36	9.28
4.3 NEPA permitting (\$6 mil. for EIS, \$1 mil for EA)	0	0	0
4.4 Preparation for operations (100% of 3.0)	6,868	2.64	67.7
4.5 Project management (10% of 4.1 through 4.4)	922	0.35	9.09
5.0 Operating and maintenance costs			
5.1 Annual operating costs	3,395	1.31	49.4
5.2 Annual utility costs	202	0.08	2.94
5.3 Annual material costs	129	0.05	1.87
5.4 Annual maintenance costs	1,768	0.68	25.7
5.5 Contingency (25% of 5.1 through 5.4)	1,374	0.53	20.0
Subtotal	6,868	2.64	100
Total 20-year O&M cost (20 x subtotal)	137,360	52.81	----
6.0 Decontamination & decommissioning	10,624	4.08	100
7.0 Pre-operations (1.0 + 2.0 + 4.0)	18,074	6.95	100
8.0 EG&G 20-year life-cycle cost estimate (3.0 + 5.0 + 6.0 + 7.0)	260,121	100	100

Source: Based on information obtained by KEI from MK-Environmental

TABLE 3-12
VITRIFICATION COST COMPONENTS:
LLW/MLLW FACILITY (455 KG/HR, ALPHA)

COST COMPONENT	COMPONENT COST (\$000)	PER CENT EG&G LIFE- CYCLE COSTS	PER CENT COST COMPONENT
1.0 Studies and bench-scale test costs	3,163	0.61	100
1.1 Manpower costs during research	1,800	0.35	56.9
1.2 Equipment costs	100	0.02	3.16
1.3 Installation costs	400	0.08	12.6
1.4 Project management before Title I (10% of 1.1 through 1.3)	230	0.04	7.27
1.5 Contingency (25% of 1.1 through 1.4)	633	0.12	20.0
2.0 Demonstration costs	4,769	0.91	100
2.1 Manpower costs during demonstration	2,400	0.46	50.3
2.2 Design cost (30% of 2.5)	244	0.05	5.12
2.3 Inspection cost (7% of 2.5)	57	0.01	1.19
2.4 Project management (10% of 2.5)	81	0.02	1.70
2.5 Construction cost	813	0.16	17.0
2.5.1 Building structure cost	80	0.02	1.68
2.5.2 Equipment costs	550	0.11	11.5
2.5.3 Indirect (29% of 2.5.1 & 2.5.2)	183	0.04	3.84
2.6 Construction management (17% of 2.5)	139	0.03	2.91
2.7 Management reserve (10% of 2.5)	81	0.02	1.70
2.8 Contingency (25% of 2.1 through 2.7)	954	0.18	20.0
3.0 Production facility construction costs	183,064	35.11	100
3.1 Design cost (12% of 3.4)	11,404	2.19	6.23
3.2 Inspection cost (7% of 3.4)	6,653	1.28	3.63
3.3 Project management (10% of 3.4)	9,504	1.82	5.19
3.4 Construction cost	95,036	18.23	51.9
3.4.1 Building structure costs	37,763	7.24	20.6
3.4.2 Equipment costs	35,908	6.89	19.6
3.4.4 Indirect (29% of 3.4.1 & 3.4.2)	21,365	4.10	11.7
3.5 Construction management (17% of 3.4)	16,251	3.12	8.88
3.6 Management reserve (10% of 3.4)	9,504	1.82	5.19
3.7 Contingency (25% of 3.1 through 3.5)	34,712	6.66	19.0
4.0 Operations budget funded activities	21,184	4.03	100
4.1 Conceptual design (1.5% of 3.0)	2,746	0.53	13.0
4.2 Safety assurance (1% of 3.0)	1,831	0.35	8.64
4.3 NEPA permitting (\$6 mil. for EIS, \$1 mil. for EA)	0	0	0
4.4 Preparation for operations (100% of 5.0)	14,681	2.82	69.3
4.5 Project management (10% of 4.1 through 4.4)	1,926	0.37	9.09

TABLE 3-12 (CONT.)
VITRIFICATION COST COMPONENTS:
455 KG/HR LLW/MLLW FACILITY (ALPHA)

COST COMPONENT	COMPONENT COST (\$000)	PER CENT OF EG&G LIFE-CYCLE COSTS	PER CENT COST COMPONENT
5.0 Operating and maintenance costs			
5.1 Annual operating costs	4,508	0.86	30.7
5.2 Annual utility costs	202	0.04	1.38
5.3 Annual material costs	127	0.02	0.865
5.4 Annual maintenance costs	6,908	1.32	47.1
5.5 Contingency (25% of 5.1 through 5.4)	2,936	0.56	20.0
5.6 Subtotal	14,681	2.82	100
5.7 Total 20-year O&M cost (20 times 5.0)	293,620	56.31	----
6.0 Decontamination & decommissioning	15,625	3.00	100
7.0 Pre-operations (1.0 + 2.0 + 4.0)	29,116	5.58	100
8.0 EG&G 20-year life-cycle cost estimate (3.0 + 5.0 + 6.0 + 7.0)	521,425	100.0	100

Source: Based on information obtained by KEI from MK-Environmental

APPENDIX TABLE 3-13
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
1.0 Prepare and feed incoming waste			2966		855	3821
Bulk solids dump hopper	1	60	60	15	15	75
Shredding system	1	880	880	176	176	1056
Waste prep crane	1	525	525	105	105	630
Size reduction table with tools	1	300	300	60	60	360
Drum/bin conveyor	20	6	120	1	20	140
Dust collection assembly	1	120	120	15	15	135
Allowance for piping/mechanical	Lot	602	602	235	235	837
Allowance for electrical/control	Lot	301	301	196	196	497
Calibration, testing & startup	Lot	58	58	33	33	91
2.0 Melter			6042		1791	7833
Melter	1					
Melter feed assembly	1					
Melter oxygen feed controller	1					
Melter inlet air blower	1					
Melter discharge system	1					
Melter room temp. monitoring & cooling	1					
Melter vacuum pumps	1					
Melter slag/ingot vacuum chamber	1					
Melter hearth removal system	2					
Complete package per above detail	Lot	4000	4000	800	800	4800
Monorail hoist	1	85	85	20	20	105
Allowance for mechanical/piping	Lot	1226	1226	492	492	1718
Allowance for electrical/control	Lot	613	613	410	410	1023
Calibration, testing & startup	Lot	118	118	69	69	187
3.0 Cool melter			444		153	597
Melter cooling water unit	1					
Cooling water pump 150 GPM	1					
Cooling water pump 200 GPM	1					
Elevated water tank	1					
Complete package per above detail	Lot	300	300	70	70	370
Allowance for piping/mechanical	Lot	90	90	42	42	132
Allowance for electrical/control	Lot	45	45	35	35	80
Calibration, testing & startup	Lot	9	9	6	6	15

APPENDIX TABLE 3-13 (CONT.)
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
4.0 Prepare and feed soil			769		270	1039
Melter soil feeder	1	150	150	30	30	180
Dryer	Lot	180	180	36	36	216
Soil day tank	1	30	30	8	8	38
Soil storage silos	2	65	130	20	40	170
Soil transfer pump	1	30	30	10	10	40
Allowance for piping/mechanical	Lot	156	156	74	74	230
Allowance for electrical/control	Lot	78	78	62	62	140
Calibration, testing & startup	Lot	15	15	10	10	25
5.0 Slag cooling & packaging			1021		292	1313
Metal canister capper	1	150	150	30	30	180
Canister decon unit	1	70	70	9	9	79
Canister cooling system	1	200	200	40	40	240
Canister conveyor	30	4	120	1	30	150
Grouting unit	1	150	150	25	25	175
Allowance for piping/mechanical	Lot	207	207	80	80	287
Allowance for electrical/control	Lot	104	104	67	67	171
Calibration, testing & startup	Lot	20	20	11	11	31
6.0 Air pollution control system			2879		1184	4063
Dry off-gas system			2287		462	2749
Primary ceramic filters	2	160	320	32	64	384
Secondary ceramic filters	2	160	320	32	64	384
Interconnecting ducts	Lot	200	200	40	40	240
Filter element removing crane	1	220	220	20	20	240
Filter element crusher	1	600	600	120	120	720
HEPA filtration system	6	52	312	10	60	372
Blowers	1	20	20	4	4	24
Stack monitors	1	275	275	85	85	360
Stack	1	20	20	5	5	25
Wet off-gas system			592		722	1314
Scrubber	1					
Scrubber bottom tank	1					
Scrubber pump	1					
Demister No. 1	1					
Condenser	1					
Demister No. 2	1					
Reheater	1					
Complete package per above	Lot	400	400	80	80	480
Allowance for piping/ mech.	Lot	120	120	325	325	445
Allowance for electrical/ con.	Lot	60	60	271	271	331
Calib., testing & startup	Lot	12	12	46	46	58

APPENDIX TABLE 3-13 (CONT.)
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
7.0 Prepare and feed caustic			592		175	767
Lime storage silo	1					
Lime feeder	1					
Caustic day tank	1					
Package system per above	Lot	400	400	80	80	480
Allowance for piping/mechanical	Lot	120	120	48	48	168
Allowance for electrical/control	Lot	60	60	40	40	100
Calibration, testing & startup	Lot	12	12	7	7	19
8.0 Electrical & control			751		353	1104
Control panel—FT	30	10	300	2	60	360
Motor control center	70	1.5	105	0.5	35	140
Stand-by emergency power	1	230	230	80	80	310
Allowance for piping/mechanical	Lot	6	6	53	53	59
Allowance for electrical/control	Lot	95	95	105	105	200
Calibration, testing & startup	Lot	15	15	20	20	35
9.0 Utilities & mechanical			577		262	839
Instrument air package	Lot	90	90	25	25	115
Compressed air package	Lot	100	100	25	25	125
Breathing air package	Lot	70	70	30	30	100
Service water	1	130	130	40	40	170
Allowance for piping/mechanical	Lot	117	117	72	72	189
Allowance for electrical/control	Lot	59	59	60	60	119
Calibration, testing & startup	Lot	11	11	10	10	21
10.0 HVAC						
Included with building costs						
11.0 Radiation monitoring			299		113	412
Air monitors	22	10	220	2	44	264
Area monitors	8	4	32	1.5	12	44
Allowance for piping/mechanical	Lot	3	3	17	17	20
Allowance for electrical/control	Lot	38	38	34	34	72
Calibration, testing & startup	Lot	6	6	6	6	12

APPENDIX TABLE 3-13 (CONT.)
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, NON-ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
12.0 Other equipment			452		109	561
Fire suppression system	7	30	210	5	35	241
Emergency shower & decon station	Lot	35	35	7	7	42
Sump pump system	4	15	60	2	8	68
Allowance for piping/mechanical	Lot	92	92	30	30	122
Allowance for electrical/control	Lot	46	46	25	25	71
Calibration, testing & startup	Lot	9	9	4	4	13
TOTAL						22349

Source: Chuck Biagi, Morrison Knudsen Corp.

TABLE 3-14
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
1.0 Prepare and Feed Incoming Waste			5304		1503	6807
Bulk solids dump hopper	1	90	90	15	15	105
Shredding system	1	1320	1320	260	260	1580
Waste prep crane	1	788	788	105	105	893
Master-slave manipulator	2	65	130	15	30	160
Size reduction table with tools	1	450	450	60	60	510
Drum/bin conveyor	20	6	120	1	20	140
Shield window	2	130	260	44	88	348
CCTV	6	10	60	2	12	72
Airlock	2	124	248	38	78	326
Dust collection assembly	1	120	120	20	20	140
Allowance for piping/mechanical	Lot	1076	1076	413	413	1489
Allowance for electrical/control	Lot	538	538	344	344	882
Calibration, testing & startup	Lot	104	104	58	58	162
2.0 Melter			10744		2376	13120
Melter	1					
Melter feed assembly	1					
Melter oxygen feed controller	1					
Melter inlet air blower	1					
Melter discharge system	1					
Melter room temp. monitoring & cooling	1					
Melter vacuum pumps	1					
Melter slag/ingot vacuum chamber	1					
Melter hearth removal system	2					
Complete package per above detail	Lot	6000	6000	800	800	6800
Maintenance crane (5 TN)	1	450	450	60	60	510
Monorail hoist (5 TN)	1	128	128	20	20	148
Shield windows	1	130	130	40	40	170
CCTV	6	10	60	2	12	72
Airlock	4	124	496	39	156	652
Allowance for mechanical/piping	Lot	2179	2179	653	653	2832
Allowance for electrical/control	Lot	1090	1090	544	544	1634
Calibration, testing & startup	Lot	211	211	91	91	302
3.0 Cool melter			444		153	597
Melter cooling water unit	1					
Cooling water pump 150 GPM	1					
Cooling water pump 200 GPM	1					
Elevated water tank	1					
Complete package per above detail	Lot	300	300	70	70	370

APPENDIX TABLE 3-14 (CONT.)
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
3.0 Cool melter (Cont.)						
Allowance for piping/mechanical	Lot	90	90	42	42	132
Allowance for electrical/control	Lot	45	45	35	35	80
Calibration, testing & startup	Lot	9	9	6	6	15
4.0 Prepare and feed soil			769		270	1039
Melter soil feeder	1	150	150	30	30	180
Dryer	Lot	180	180	36	36	216
Soil day tank	1	30	30	8	8	38
Soil storage silos	2	65	130	20	40	170
Soil transfer pump	1	30	30	10	10	40
Allowance for piping/mechanical	Lot	156	156	74	74	230
Allowance for electrical/control	Lot	78	78	62	62	140
Calibration, testing & startup	Lot	15	15	10	10	25
5.0 Slag cooling & packaging			3227		891	4118
Metal canister capper	1	225	225	30	30	255
Canister decon unit	1	105	105	9	9	114
Canister cooling system	2	300	600	40	80	680
Canister conveyor	30	4	120	1	30	150
Crane	1	450	450	60	60	510
Airlock	2	124	248	39	78	326
Shield windows	2	130	260	44	88	348
Grouting unit	1	150	150	25	25	175
CCTV	4	6	24	2	8	32
Allowance for piping/mechanical	Lot	655	655	245	245	900
Allowance for electrical/control	Lot	327	327	204	204	531
Calibration, testing & startup	Lot	63	63	34	34	97
6.0 Air pollution control system			5623		2221	7844
Dry off-gas system			4325		1244	5569
Primary ceramic filters	2	240	480	32	64	544
Secondary ceramic filters	2	240	480	32	64	544
Interconnecting ducts	Lot	300	300	40	40	340
Filter element removing crane	1	330	330	20	20	350
Crane	1	450	450	60	60	510
Filter element crusher	1	900	900	120	120	1020
HEPA filtration system	6	78	468	10	60	528
Blowers	1	30	30	4	4	34
Stack monitors	1	275	275	85	85	360
Stack	1	20	20	5	5	25

APPENDIX TABLE 3-14 (CONT.)
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
6.0 Air pollution control system (Cont.)						
Wet off-gas system			1298		977	2275
Scrubber	1					
Scrubber bottom tank	1					
Scrubber pump	1					
Demister No. 1	1					
Condenser	1					
Demister No. 2	1					
Reheater	1					
Complete package per above	Lot	600	600	80	80	680
CCTV	3	10	30	2	6	36
Airlock	2	124	248	39	78	326
Allowance for piping/ mech.	Lot	263	263	412	412	675
Allowance for electrical/ con.	Lot	132	132	343	343	475
Calib., testing & startup	Lot	25	25	58	58	83
7.0 Prepare and feed caustic			592		175	767
Lime storage silo	1					
Lime feeder	1					
Caustic day tank	1					
Package system per above	Lot	400	400	80	80	480
Allowance for piping/mechanical	Lot	120	120	48	48	168
Allowance for electrical/control	Lot	60	60	40	40	100
Calibration, testing & startup	Lot	12	12	7	7	19
8.0 Electrical & control			760		358	1118
Control panel—FT	30	10	300	2	60	360
Motor control center	75	1.5	113	0.5	38	151
Standby emergency power	1	230	230	80	80	310
Allowance for piping/mechanical	Lot	6	6	53	53	59
Allowance for electrical/control	Lot	96	96	107	107	203
Calibration, testing & startup	Lot	15	15	20	20	35
9.0 Utilities & mechanical			577		262	839
Instrument air package	Lot	90	90	25	25	115
Compressed air package	Lot	100	100	25	25	125
Breathing air package	Lot	70	70	30	30	100
Service water	1	130	130	40	40	170
Allowance for piping/mechanical	Lot	117	117	72	72	189
Allowance for electrical/control	Lot	59	59	60	60	119
Calibration, testing & startup	Lot	11	11	10	10	21

APPENDIX TABLE 3-14 (CONT.)
DETAILED LIST OF EQUIPMENT AND INSTALLATION COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR, ALPHA)

Description	Materials & Equip.			Installation Cost		
	Qty.	Unit Cost, \$000	Amt., \$000	Unit Cost, \$000	Amt., \$000	Total Unit Oper.
10.0 HVAC						
Included with building costs						
11.0 Radiation monitoring			299		113	412
Air monitors	22	10	220	2	44	264
Area monitors	8	4	32	1.5	12	44
Allowance for piping/mechanical	Lot	3	3	17	17	20
Allowance for electrical/control	Lot	38	38	34	34	72
Calibration, testing & startup	Lot	6	6	6	6	12
12.0 Other equipment			452		109	561
Fire suppression system	7	30	210	5	35	241
Emergency shower & decon station	Lot	35	35	7	7	42
Sump pump system	4	15	60	2	8	68
Allowance for piping/mechanical	Lot	92	92	30	30	122
Allowance for electrical/control	Lot	46	46	25	25	71
Calibration, testing & startup	Lot	9	9	4	4	13
TOTAL						35311

Source: Chuck Biagi, Morrison Knudsen Corp.

APPENDIX TABLE 3-15
VITRIFICATION EQUIPMENT/INSTALLATION COST ANALYSIS

UNIT OPERATION DESCRIPTION	NON-ALPHA		ALPHA	
	EQUIP.	INSTAL.	EQUIP.	INSTAL.
	(PER CENT, %)			
1.0 Prepare and feed incoming waste	77.6	22.4	77.9	22.1
Bulk solids dump hopper	80.0	20.0	85.7	14.3
Shredding system	83.3	16.7	83.5	16.5
Waste prep crane	83.3	16.7	88.2	11.8
Size reduction table with tools	83.3	16.7	88.2	11.8
Drum/bin conveyor	85.7	14.3	85.7	14.3
Dust collection assembly	88.9	11.1	85.7	14.3
Allowance for piping/mechanical	71.9	28.1	72.3	27.7
Allowance for electrical/control	60.6	39.4	61.0	39.0
Calibration, testing & startup	63.7	36.3	64.2	35.8
Master-slave manipulator	--	--	81.3	18.8
Shield window	--	--	74.7	25.3
CCTV	--	--	83.3	16.7
Airlock	--	--	76.1	23.9
2.0 Melter	77.1	22.9	81.9	18.1
Melter				
Melter feed assembly				
Melter oxygen feed controller				
Melter inlet air blower				
Melter discharge system				
Melter room temp. monitoring & cooling				
Melter vacuum pumps				
Melter slag/ingot vacuum chamber				
Melter hearth removal system				
Complete package per above detail	83.3	16.7	88.2	11.8
Maintenance crane (5 TN)	--	--	88.2	11.8
Monorail hoist (5 TN)	81.0	19.0	86.5	13.5
Allowance for mechanical/piping	71.4	28.6	76.9	23.1
Allowance for electrical/control	59.9	40.0	66.7	33.3
Calibration, testing & startup	63.1	36.9	69.9	30.1
Shield windows	0	0	76.5	23.5
CCTV	0	0	83.3	16.7
Airlock	0	0	76.1	23.9
3.0 Cool melter	74.4	25.6	74.4	25.6
Melter cooling water unit				
Cooling water pump 150 GPM				
Cooling water pump 200 GPM				

APPENDIX TABLE 3-15 (CONT.)
VITRIFICATION EQUIPMENT/INSTALLATION COST BREAKDOWN

UNIT OPERATION DESCRIPTION	NON-ALPHA		ALPHA	
	EQUIP.	INSTAL.	EQUIP.	INSTAL.
	(PER CENT, %)			
3.0 Cool melter (Cont.)				
Elevated water tank				
Complete package per above detail	81.1	18.9	81.1	18.9
Allowance for piping/mechanical	68.2	31.8	68.2	31.8
Allowance for electrical/control	56.3	43.7	56.3	43.8
Calibration, testing & startup	60.0	40.0	60.0	40.0
4.0 Prepare and feed soil	74.0	26.0	74.0	26.0
Melter soil feeder	83.3	16.7	83.3	16.7
Dryer	83.3	16.7	83.3	16.7
Soil day tank	78.9	21.1	78.9	21.1
Soil storage silos	76.5	23.5	76.5	23.5
Soil transfer pump	75.0	25.0	75.0	25.0
Allowance for piping/mechanical	67.8	14.2	67.8	14.2
Allowance for electrical/control	55.7	44.3	55.7	44.3
Calibration, testing & startup	60.0	40.0	60.0	40.0
5.0 Slag cooling & packaging	77.8	22.2	78.4	21.6
Metal canister capper	83.3	16.7	88.2	11.8
Canister decon unit	88.6	11.4	92.1	7.9
Canister cooling system	83.3	16.7	88.2	11.8
Canister conveyor	80.0	20.0	80.0	20.0
Grouting unit	85.7	14.3	85.7	14.3
Allowance for piping/mechanical	72.1	27.9	72.8	27.2
Allowance for electrical/control	60.8	39.2	61.6	38.4
Calibration, testing & startup	64.5	35.5	64.9	35.1
Crane	0	0	88.2	11.8
Airlock	0	0	76.1	23.9
Shield windows	0	0	74.7	25.3
CCTV	0	0	75.0	25.0
6.0 Air pollution control system	70.9	29.1	71.7	28.3
Dry off-gas system	83.2	16.8	77.7	22.3
Primary ceramic filters	83.3	16.7	88.2	11.8
Secondary ceramic filters	83.3	16.7	88.2	11.8
Interconnecting ducts	83.3	16.7	88.2	11.8
Filter element removing crane	91.7	8.3	94.3	5.7
Crane	0	0	88.2	11.8
Filter element crusher	83.3	16.7	88.2	11.8
HEPA filtration system	83.9	16.1	88.6	11.4
Blowers	83.3	16.7	88.2	11.8
Stack monitors	76.4	23.6	76.4	23.6
Stack	80.0	20.0	80.0	20.0

APPENDIX TABLE 3-15 (CONT.)
VITRIFICATION EQUIPMENT/INSTALLATION COST BREAKDOWN

UNIT OPERATION DESCRIPTION	NON-ALPHA		ALPHA	
	EQUIP.	INSTAL.	EQUIP.	INSTAL.
	(PER CENT, %)			
Wet off-gas system	45.1	54.9	57.1	42.9
Scrubber				
Scrubber bottom tank				
Scrubber pump				
Demister No. 1				
Condenser				
Demister No. 2				
Reheater				
Complete package per above	83.3	16.7	88.3	11.8
Allowance for piping/ mech.	27.0	73.0	39.0	61.0
Allowance for electrical/ con.	18.1	81.9	27.8	72.2
Calib., testing & startup	20.7	79.3	30.1	69.9
CCTV	0	0	83.3	16.7
Airlock	0	0	76.1	23.9
7.0 Prepare and feed caustic	77.2	22.8	77.2	22.8
Lime storage silo				
Lime feeder				
Caustic day tank				
Package system per above	83.3	16.7	83.3	16.7
Allowance for piping/mechanical	71.4	28.6	71.4	28.6
Allowance for electrical/control	60.0	40.0	60.0	40.0
Calibration, testing & startup	63.2	36.8	63.2	36.8
8.0 Electrical & control	68.0	32.0	68.0	32.0
Control panel—FT	83.3	16.7	83.3	16.7
Motor control center	75.0	25.0	74.8	25.2
Standby emergency power	74.2	25.8	74.2	25.8
Allowance for piping/mechanical	10.2	89.8	10.2	89.8
Allowance for electrical/control	47.5	52.5	47.3	52.7
Calibration, testing & startup	42.9	57.1	42.9	57.1
9.0 Utilities & mechanical	68.8	31.2	68.8	31.2
Instrument air package	78.3	21.7	78.3	21.7
Compressed air package	80.0	20.0	80.0	20.0
Breathing air package	70.0	30.0	70.0	30.0
Service water	76.5	23.5	76.5	23.5
Allowance for piping/mechanical	61.9	38.1	61.9	38.1
Allowance for electrical/control	49.6	50.4	49.6	50.4
Calibration, testing & startup	52.4	47.6	52.4	47.6
10.0 HVAC				
Included with building costs				

TABLE 3-15 (CONT.)
VITRIFICATION EQUIPMENT/INSTALLATION COST BREAKDOWN

UNIT OPERATION DESCRIPTION	NON-ALPHA		ALPHA	
	EQUIP.	INSTAL.	EQUIP.	INSTAL.
	(PER CENT, %)			
11.0 Radiation monitoring	75.6	27.4	75.6	27.4
Air monitors	83.3	16.7	83.3	16.7
Area monitors	72.7	27.3	72.7	27.3
Allowance for piping/mechanical	15.0	85.0	15.0	85.0
Allowance for electrical/control	52.8	47.2	52.8	47.2
Calibration, testing & startup	50.0	50.0	50.0	50.0
12.0 Other equipment	80.6	19.4	80.6	19.4
Fire suppression system	87.1	12.9	87.1	12.9
Emergency shower & decon station	83.3	16.7	83.3	16.7
Sump pump system	88.2	11.8	88.2	11.8
Allowance for piping/mechanical	75.4	24.6	75.4	24.6
Allowance for electrical/control	64.8	35.2	64.8	35.2
Calibration, testing & startup	69.2	30.8	69.2	30.8
TOTAL	75.1	24.9	77.3	22.7

Source: KEI

TABLE 3-16
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
1.0 Prepare and feed incoming waste	3821	17.1	100	6807	18.3	100
Bulk solids dump hopper	75		1.96	105		1.54
Shredding system	1056		27.6	1580		23.2
Waste prep crane	630		16.5	893		13.1
Size reduction table with tools	360		9.42	510		7.49
Drum/bin conveyor	140		3.66	140		2.06
Dust collection assembly	135		3.53	140		2.06
Allowance for piping/mechanical	837		21.9	1489		21.9
Allowance for electrical/control	497		13.0	882		13.0
Calibration, testing & startup	91		2.38	162		2.38
Master-slave manipulator				160		2.35
Shield window				348		5.11
CCTV				72		1.06
Airlock				326		4.79
2.0 Melter	7833	35.0	100	13120	35.2	100
Melter						
Melter feed assembly						
Melter oxygen feed controller						
Melter inlet air blower						
Melter discharge system						
Melter room temp. monitoring & cooling						
Melter vacuum pumps						
Melter slag/ingot vacuum chamber						
Melter hearth removal system						
Complete package per above detail	4800		61.3	6800		51.8
Maintenance crane (5 TN)	---		---	510		3.89
Monorail hoist (5 TN)	105		1.34	148		1.13
Allowance for mechanical/piping	1718		21.9	2832		21.6
Allowance for electrical/control	1023		13.1	1634		12.5
Calibration, testing & startup	187		2.39	302		2.30
Shield windows				170		1.30
CCTV				72		0.55
Airlock				652		4.97

TABLE 3-16 (CONT.)
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
3.0 Cool melter	597	2.67	100	597	1.60	100
Melter cooling water unit						
Cooling water pump 150 GPM						
Cooling water pump 200 GPM						
Elevated water tank						
Complete package per above detail	370		62.0	370		62.0
Allowance for piping/mechanical	132		22.1	132		22.1
Allowance for electrical/control	80		13.4	80		13.4
Calibration, testing & startup	15		2.51	15		2.51
4.0 Prepare and feed soil	1039	4.65	100	1039	2.79	100
Melter soil feeder	180		17.3	180		17.3
Dryer	216		20.8	216		20.8
Soil day tank	38		3.66	38		3.66
Soil storage silos	170		16.4	170		16.4
Soil transfer pump	40		3.85	40		3.85
Allowance for piping/mechanical	230		22.1	230		22.1
Allowance for electrical/control	140		13.5	140		13.5
Calibration, testing & startup	25		2.41	25		2.41
5.0 Slag cooling & packaging	1313	5.87	100	4118	11.1	100
Metal canister capper	180		13.7	225		5.46
Canister decon unit	79		6.01	114		2.77
Canister cooling system	240		18.3	680		16.5
Canister conveyor	150		11.4	150		3.64
Grouting unit	175		13.3	510		12.4
Allowance for piping/mechanical	287		21.9	900		21.9
Allowance for electrical/control	171		13.0	531		12.9
Calibration, testing & startup	31		2.36	97		2.36
Crane				510		12.4
Airlock				326		7.92
Shield windows				348		8.45
CCTV				175		4.25

TABLE 3-16 (CONT.)
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
6.0 Air pollution control system	4063	18.2	100	7844	21.1	100
Dry off-gas system	2749		67.7/100	5569		71.0/100
Primary ceramic filters	384		9.45/14.0	544		6.94/9.77
Secondary ceramic filters	384		9.45/14.0	544		6.94/9.77
Interconnecting ducts	240		5.91/8.73	340		4.33/6.11
Filter element removing crane	240		5.91/8.73	350		4.46/6.28
Crane	--		--	510		6.50/9.16
Filter element crusher	720		17.7/26.2	1020		13.0/18.3
HEPA filtration system	372		9.16/13.5	528		6.73/9.48
Blowers	24		0.59/0.87	34		0.43/0.61
Stack monitors	360		8.86/13.1	360		4.59/6.46
Stack	25		0.62/0.91	25		0.32/0.45
Wet off-gas system	1314		32.3/100	2275		29.0/100
Scrubber						
Scrubber bottom tank						
Scrubber pump						
Demister No. 1						
Condenser						
Demister No. 2						
Reheater						
Complete package per above	480		11.8/36.5	680		8.67/29.9
Allowance for piping/ mech.	445		11.0/33.9	675		8.61/29.7
Allowance for electrical/ con.	331		8.15/25.2	475		6.06/20.9
Calib., testing & startup	58		1.43/4.41	83		1.06/3.65
CCTV				36		0.46/1.58
Airlock				326		4.16/14.3
7.0 Prepare and feed caustic	767	3.43	100	767	2.10	100
Lime storage silo						
Lime feeder						
Caustic day tank						
Package system per above	480		62.6	480		62.6
Allowance for piping/mechanical	168		21.9	168		21.9
Allowance for electrical/control	100		13.0	100		13.0
Calibration, testing & startup	19		2.48	19		2.48

TABLE 3-16 (CONT.)
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (455 KG/HR)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
8.0 Electrical & control	1104	4.94	100	1118	3.00	100
Control panel—FT	360		32.6	360		32.2
Motor control center	140		12.7	151		13.5
Standby emergency power	310		28.1	310		27.7
Allowance for piping/mechanical	59		5.34	59		5.28
Allowance for electrical/control	200		18.1	203		18.2
Calibration, testing & startup	35		3.17	35		3.13
9.0 Utilities & mechanical	839	3.75	100	839	2.25	100
Instrument air package	115		13.7	115		13.7
Compressed air package	125		14.9	125		14.9
Breathing air package	100		11.9	100		11.9
Service water	170		20.3	170		20.3
Allowance for piping/mechanical	189		22.5	189		22.5
Allowance for electrical/control	119		14.2	119		14.2
Calibration, testing & startup	21		2.50	21		2.50
10.0 HVAC						
Included with building costs						
11.0 Radiation monitoring	412	1.84	100	412	1.11	100
Air monitors	264		64.1	264		64.1
Area monitors	44		10.7	44		10.7
Allowance for piping/mechanical	20		4.86	20		4.85
Allowance for electrical/control	72		17.5	72		17.5
Calibration, testing & startup	12		2.91	12		2.91
12.0 Other equipment	561	2.51	100	561	1.51	100
Fire suppression system	241		43.0	241		43.0
Emergency shower & decon station	42		7.49	42		7.49
Sump pump system	68		12.1	68		12.1
Allowance for piping/mechanical	122		21.7	122		21.7
Allowance for electrical/control	71		12.7	71		12.7
Calibration, testing & startup	13		2.32	13		2.32
TOTAL	22349	100	100	37222	100	100

Source: KEI (Based on EG&G cost estimate)

**APPENDIX TABLE 3-17
VITRIFICATION BUILDING COST SUMMARY (455 KG/HR)**

UNIT OPERATION	BUILDING AREA, FT²				TOTAL COST, \$
	ADMIN	MED. HAZ.	MAINT	ALPHA	
NON-ALPHA					
Prepare and feed incoming waste		375	1800		1598
Melter		500	2400		2130
Cool melter		725			305
Prepare and feed soil		725			305
Slag cooling & packaging		625	3000		2663
Air pollution control		1562	7500		6656
Prepare and feed caustic		725			305
Electrical & control		725			305
Utilities & mechanical		725			305
HVAC		2224			934
Radiation monitoring					
Other equipment					
TOTAL		8911	14700		15,506
PER CENT		38	62		
ALPHA					
Prepare and feed incoming waste		413	825	1980	4133
Melter		563	1125	2700	5636
Cool melter		1088			457
Prepare and feed soil		1088			457
Slag cooling & packaging		700	1400	3360	7014
Air pollution control		1763	3525	8460	17660
Prepare and feed caustic		1088			457
Electrical & control		1631			685
Utilities & mechanical		1631			685
HVAC		1378			579
Radiation monitoring					0
Other equipment					0
TOTAL		11343	6875	16500	37,763
PER CENT		33	20	47	

Source: Chuck Biagi and Belinda Wong, Morrison Knudsen Corp.

TABLE 3-18
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (7,000 KG/HR*)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
1.0 Prepare and feed incoming waste	21773	17.1	100	38787	18.3	100
Bulk solids dump hopper	427		1.96	598		1.54
Shredding system	6017		27.6	9003		23.2
Waste prep crane	3590		16.5	5088		13.1
Size reduction table with tools	2051		9.42	2906		7.49
Drum/bin conveyor	798		3.67	798		2.06
Dust collection assembly	769		3.53	798		2.06
Allowance for piping/mechanical	4769		21.9	8485		21.9
Allowance for electrical/control	2832		13.0	5026		13.0
Calibration, testing & startup	519		2.38	923		2.38
Master-slave manipulator				912		2.35
Shield window				1983		5.11
CCTV				410		1.06
Airlock				1858		4.79
2.0 Melter	44634	35.0	100	74760	35.2	100
Melter						
Melter feed assembly						
Melter oxygen feed controller						
Melter inlet air blower						
Melter discharge system						
Melter room temp. monitoring & cooling						
Melter vacuum pumps						
Melter slag/ingot vacuum chamber						
Melter hearth removal system						
Complete package per above detail	27351		61.3	38748		51.8
Maintenance crane (5 TN)	---		---	2906		3.89
Monorail hoist (5 TN)	598		1.34	843		1.13
Allowance for mechanical/piping	9789		21.9	16137		21.6
Allowance for electrical/control	5829		13.1	9311		12.5
Calibration, testing & startup	1066		2.39	1721		2.30
Shield windows				969		1.30
CCTV				410		0.55
Airlock				3715		4.97
3.0 Cool melter	3402	2.67	100	3402	1.60	100
Melter cooling water unit						
Cooling water pump 150 GPM						
Cooling water pump 200 GPM						
Elevated water tank						
Complete package per above detail	2108		62.0	2108		62.0

TABLE 3-18 (CONT.)
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (7,000 KG/HR*)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
Allowance for piping/mechanical	752		22.1	752		22.1
Allowance for electrical/control	456		13.4	456		13.4
Calibration, testing & startup	85		2.51	85		2.51
4.0 Prepare and feed soil	5920	4.65	100	5920	2.79	100
Melter soil feeder	1026		17.3	1026		17.3
Dryer	1231		20.8	1231		20.8
Soil day tank	217		3.67	217		3.67
Soil storage silos	969		16.4	969		16.4
Soil transfer pump	228		3.85	228		3.85
Allowance for piping/mechanical	1311		22.1	1311		22.1
Allowance for electrical/control	798		13.5	798		13.5
Calibration, testing & startup	142		2.41	142		2.41
5.0 Slag cooling & packaging	7482	5.87	100	23465	11.1	100
Metal canister capper	1026		13.7	1282		5.46
Canister decon unit	450		6.01	650		2.77
Canister cooling system	1368		18.3	3874		16.5
Canister conveyor	855		11.4	855		3.64
Grouting unit	997		13.3	997		4.25
Allowance for piping/mechanical	1635		21.9	5128		21.9
Allowance for electrical/control	974		13.0	3026		12.9
Calibration, testing & startup	177		2.36	553		2.36
Crane				2906		12.4
Airlock				1858		7.92
Shield windows				1983		8.45
CCTV				182		0.78
6.0 Air pollution control system	23152	18.2	100	44696	21.1	100
Dry off-gas system	15664		67.7/100	31733		71.0/100
Primary ceramic filters	2188		9.45/14.0	3100		6.94/9.77
Secondary ceramic filters	2188		9.45/14.0	3100		6.94/9.77
Interconnecting ducts	1368		5.91/8.73	1937		4.33/6.10
Filter element removing crane	1368		5.91/8.73	1994		4.46/6.28
Crane	---		---	2906		6.50/9.16
Filter element crusher	4103		17.7/26.2	5812		13.0/18.3
HEPA filtration system	2120		9.16/13.5	3009		6.73/9.48
Blowers	137		0.59/0.87	194		0.43/0.61
Stack monitors	2051		8.85/13.1	2051		4.59/6.46
Stack	142		0.61/0.91	142		0.32/0.45

TABLE 3-18 (CONT.)
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (7,000 KG/HR*)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
6.0 Air pollution control system (Cont.)						
Wet off-gas system	7487		32.3/100	12963		29.0/100
Scrubber						
Scrubber bottom tank						
Scrubber pump						
Demister No. 1						
Condenser						
Demister No. 2						
Reheater						
Complete package per above	2735		11.8/36.5	3875		8.67/29.9
Allowance for piping/ mech.	2536		11.0/33.9	3846		8.61/29.7
Allowance for electrical/ con.	1886		8.15/25.2	2707		6.06/20.9
Calib., testing & startup	330		1.43/4.41	473		1.06/3.65
CCTV				205		0.46/1.58
Airlock				1858		4.16/14.3
7.0 Prepare and feed caustic	4371	3.43	100	4371	2.10	100
Lime storage silo						
Lime feeder						
Caustic day tank						
Package system per above	2735		62.6	2735		62.6
Allowance for piping/mechanical	957		21.9	957		21.9
Allowance for electrical/control	570		13.0	570		13.0
Calibration, testing & startup	108		2.48	108		2.48
8.0 Electrical & control	6291	4.94	100	6371	3.00	100
Control panel—FT	2051		32.6	2051		32.2
Motor control center	798		12.7	860		13.5
Standby emergency power	1766		28.1	1766		27.7
Allowance for piping/mechanical	336		5.34	336		5.28
Allowance for electrical/control	1140		18.1	1157		18.2
Calibration, testing & startup	199		3.17	199		3.13
9.0 Utilities & mechanical	4781	3.75	100	4781	2.25	100
Instrument air package	655		13.7	655		13.7
Compressed air package	712		14.9	712		14.9
Breathing air package	570		11.9	570		11.9
Service water	969		20.3	969		20.3
Allowance for piping/mechanical	1077		22.5	1077		22.5
Allowance for electrical/control	678		14.2	678		14.2
Calibration, testing & startup	120		2.50	120		2.50

TABLE 3-18 (CONT.)
ANALYSIS OF TOTAL INSTALLED EQUIPMENT COSTS:
LLW/MLLW VITRIFICATION FACILITY (7,000 KG/HR*)

UNIT OPERATION DESCRIPTION	NON-ALPHA			ALPHA		
	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost	Cost (\$000)	% of Total Cost, %	% of Subcom- ponent Cost
10.0 HVAC						
Included with building costs						
11.0 Radiation monitoring	2348	1.84	100	2348	1.11	100
Air monitors	1504		64.1	1504		64.1
Area monitors	251		10.7	251		10.7
Allowance for piping/mechanical	114		4.86	114		4.85
Allowance for electrical/control	410		17.5	410		17.5
Calibration, testing & startup	68		2.91	68		2.91
12.0 Other equipment	3197	2.51	100	3197	1.51	100
Fire suppression system	1373		42.9	1373		42.9
Emergency shower & decon station	239		7.48	239		7.48
Sump pump system	387		12.1	387		12.1
Allowance for piping/mechanical	695		21.7	695		21.7
Allowance for electrical/control	405		12.7	405		12.7
Calibration, testing & startup	74		2.32	74		2.32
TOTAL	127349	100	100	212097	100	100

* Scaled up to 7,019 using X/10s Rule, where X = 0.636 (facility construction)
 $\text{Cost}_{7019} = \text{Cost}_{455} \times (7019/455)^{0.636} = 5.6982 \times \text{Cost}_{455}$

Source: KEI

APPENDIX 4. PREVIOUS COST ESTIMATES

Some cost and engineering data are available for the most mature denitrification options, the high-temperature fluid-wall reactor, the glass furnace, and for the biodenitrification. A preliminary design for a production facility was completed by Thagard Research Corp. (TRC) under contract to Rockwell International. The production facility was based on the pilot-scale experimental work done by TRC. Monsanto Research Corp.-Mound completed a task for the NLLWMP on nitrate destruction using the glass furnace. The Oak Ridge Y-12 Plant has constructed a central waste treatment facility, which uses their biodenitrification process.

BIODENITRIFICATION

The information in this section was obtained from *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies* (DOE/TIC-4500, Rev. 73, March 1986). According to this report, the total nitrate load to the West End Treatment Facility (WETF) is approximately 212,000 kg of nitrate ion annually. Acid nitrate wastes contain most of the nitrate, approximately 200,000 kg/yr. Caustic waste will contain 22,000 kg/yr of nitrate ion. Coolant waste contains 300 kg/yr.

The biodenitrification reactor effluent refers to a set of continuous 26,000-gallon bioreactors on the Y-12 Plant. The nitrate content of this stream is low, 400 kg/yr, because of recovery and treatment prior to the discharge to the WETF. The Y-12 Plant operates a nitrate recovery system consisting of an acid still and aluminum nitrate crystallizer. The waste from these systems is treated in the continuous bioreactors, but residual nitrate concentrations indicate the need for further treatment at the WETF.

TOTAL COST

The total estimated cost of the WETF for denitrification was projected to be \$7,200,000. The estimated cost of the installed equipment in the WETF process building is \$3,000,000. (The total building cost is estimated at \$5,800,000.) Two tank farms are required for biodenitrification reactors at a cost of \$2,100,000 per each tank farm. The third tank farm is not required for biodenitrification so the cost was not included in the WETF denitrification cost. Only the installed equipment cost was considered rather than the total building cost to make the estimate more comparable to the TRC and MRC-Mound data.

OPERATING AND MAINTENANCE COSTS

The operating and maintenance cost of the WETF is projected to be in the range of \$2.50 to \$3.50 per gallon of waste processed, but does not include sludge disposal. The cost is essentially independent of throughput so an increase in throughput would reduce the cost per gallon. An operating crew of approximately 30 people is expected to be required to operate this facility. The unit cost of denitrification of this waste is high due to the dilute nature of the waste. Using a concentration of 212,000 kg of nitrate ion (not nitrate salt) in 2 million gallons of waste results in a cost of \$23 to \$33 per kilogram of nitrate destroyed. The facility also performs other functions such as heavy metal removal for this cost. Also, there are no further costs associated with waste packaging, shipping, or final disposal of the liquid waste stream, which is discharged into surface waterways, nor are there any expenses required to process and dry the waste stream such as required for the HTFW Reactor.

CALCINATION

One estimate of the price of nitrate destruction of INEL waste by calcination has been reported to be \$130/kg nitrate or \$37 per liter.

GROUTING

For the reference case of 1,000,000 kg of Rocky Flat waste salt annually, 1,850,000 kg of saltcrete would be produced. Portland cement costs would be \$41,000 for 370,000 kg of cement. The shipping costs for full trailers from RFP to the NTS are \$0.088/kg. The increased cost for shipping an additional 850,000 kg is \$75,000 annually.

The costs for cementitious waste forms that have been reported in the literature vary widely. These costs were summarized in *Technology Logic Diagram Input Document* (3/11/93 draft copy by Roger Spence). One source (Dole and Trauger, 1983; Kessler, 1984) estimated to be \$0.05-0.15/gallon of waste for the materials cost and \$0.10-0.50/gallon total disposal cost (including material, capital, and operating costs). Another source (Myrick, 1992) estimated a total project cost to be \$115/gallon concentrated low-level waste, which is based on solidifying 45,000 gallons of low-level waste. The cost of alumino-silicate stabilization was estimated (Bates, 1992) at \$0.90-1.78/gallon (\$190-360/yd³) to treat 15,000 cubic yards of a site demonstration waste. The direct cost of grouting has been estimated (Gimpel and Diggs, 1992) to be \$0.34-0.83/gallon (\$90-220/m³) and total costs (including disposal) to be \$4.49-7.91/gallon (\$1186-2090/m³).

NITRATE TO AMMONIA AND CERAMIC/GLASS

A preliminary design for a NAC plant to reduce the nitrate in the Hanford SSTs was done in 1992 by Dave Brashears, who estimated the costs associated with construction and operation. The analysis and cost estimates along with the assumptions used in the evaluation and a conceptual design drawing are described below. Note that this analysis did not include the cost of converting the NAC product to a glass or ceramic final waste form. This analysis was obtained by KEI from the following document: *Low-temperature Process for the Denitration of Hanford Single-shell Tank, Nitrate-based Waste Utilizing the Nitrate to Ammonia and Ceramic (NAC) Process* (DRAFT, ORNL/TM-12245, Oct. 1992).

PROCESS BASIS AND ASSUMPTIONS

The 1992 ORNL cost estimate was based on a very rough flow sheet sketch of a proposed full-scale nitrate waste treatment process at the Hanford Site in Washington State. The cost assessment was a very rough order of magnitude and much more additional definition is required before any "concrete" cost assessments can be made.

The estimate was based on a 10,000 gallon batch, single-stage stirred tank type reactor that can remove 8,500 kW of heat. That analysis also assumed the following: only the 1992 tank inventory of 125,000 tons of NO₃ would be processed around the clock at a 60 per cent availability over 20 years at a 1,200 kg NO₃/hr rate. In addition to the 10,000 gallon reactor and its associated mixing and heat exchange equipment, that analysis included a rotary vacuum dryer, a calciner for the solid product, and a catalytic burner to convert the ammonia and hydrogen that is produced to nitrogen and water vapor. The raw materials required include approximately 45,400 kg/d of aluminum metal, 2,000 l/d of 50 per cent

sodium hydroxide, and 283.2 m³/min of air for the catalytic ammonia burner. General assumptions include the following:

- Land is available.
- Utilities, sufficient electrical power, and water are available within reasonable distance (i.e., 200 LF), at the proposed site.
- Engineering, project management, construction management, and contingency have been included at levels as identified based upon previous experience with similar type processes.
- The proposed site of construction poses no problems with contamination, security, or extraordinary site difficulties.
- Dollars presented are FY92 4th quarter. No escalation for future years is included.

The estimated feed rate was based on the following assumptions:

- Only the current tank inventory of nitrate and nitrite were considered. Any nitrate added in the pretreatment (which could double the total) was considered separately.
- All nitrate will exist as nitrate and the feed will be 3.1 M nitrate. This results in an over estimate of the aluminum required. Thus the total approximately equals:

$$(125 \times 10^6 \text{ kg NO}_3 \times 1000 \text{ g/kg}) / (3.1 \text{ moles/l} \times 62 \text{ g/mole}) / 1000 \text{ l/m}^3 = 650,000 \text{ m}^3$$

- The inventory will be processed over a twenty-year period.

$$6.25 \times 10^6 \text{ kg/yr or } 32,500 \text{ m}^3/\text{yr}$$

- Around the clock operations with 60 per cent availability yields

$$32,500 \text{ m}^3/\text{yr} / (0.6 \times 365 \times 24) \text{ hrs/yr} = 6.18 \text{ m}^3/\text{hr or } 1,200 \text{ kg NO}_3/\text{hr}$$

- The feed was assumed to contain other constituents as described in the "Hanford Single-shell Tank Waste, Preliminary Pretreatment Testing of Simulated Waste" from *Proceedings of the 7th Annual DOE Model Conference on Waste Management and Environmental Restoration*, October 14-17, 1991. Although the actual chemistry is complex with multiple reactions, the overall stoichiometric reaction was assumed to be:

or

Heat of reaction = -1,142 kcal; Entropy of reaction = +0.919 cal/K

An undesirable competing reaction is: $3\text{H}_2\text{O} + 2\text{Al} \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2$

PROCESS PARAMETERS

Bench-scale tests using both sodium nitrate solutions and simulated SST waste have established the following process parameters and characteristics:

- The desired reaction temperature is between 50 and 80°C. Below 50°C the reaction is slow to start, and above 80°C it is difficult to control and leads to rapid steam production.

- A pH above 11 (preferably 12 to 13) is required to initiate and maintain a reasonable reaction rate. The addition of about 50 grams NaOH raises a 3.1 M NaNO₃ to about pH 13.
- The addition of aluminum in the form of spheres larger than 200 microns in diameter to fresh 3.1 M nitrate solution lowers the pH to below 10 and delays onset of the reaction for about 4 hours. Use of non-oxidized aluminum or fine aluminum powder avoids this reaction delay. It has also been shown that a seed of the gibbsite product from the reaction promotes instant start of the reaction.
- Although the heat of reaction was not determined, the highly exothermic nature of the process was confirmed.
- To obtain 100 ppm or less nitrate in the reactor effluent requires about twice the stoichiometric amount of aluminum (i.e., 2.3 kg Al per kg nitrate or 1.7 kg Al/kg sodium nitrate).
- Under these conditions, the resulting products per kg of nitrate destroyed are: 365 liters ammonia at standard temperature and pressure (STP), 1,450 liters hydrogen at STP, and a slurry consisting of 94 per cent gibbsite or Al(OH)₃ and 6 per cent NaAlO₂ by dry weight.
- Although the rate of reaction was not precisely determined, it was observed that about 1-2 hours were sufficient to reduce the nitrate concentration to 100 ppm or less. A 2-hour requirement was assumed.

COST ESTIMATE

Table 4-1 below summarizes the capital costs from the 1992 ORNL estimate for the NAC process.

APPENDIX TABLE 4-1 1992 ORNL NAC CAPITAL COST ESTIMATE

ITEM	FY92 4TH QTR COST, \$
Total equipment and facilities (process equipment, utilities, and support equipment)	7,885,000
Construction management @ 25%	1,915,000
Engineering @ 25%	2,450,000
Project management @ 10%	1,200,000
Subtotal	13,450,000
Contingency @ 50%	6,750,000
Total	20,200,000

Table 4-2 below summarizes the annual-cost estimate from the ORNL assessment, which includes capital and operating and maintenance costs. Based on these estimates, the total annual cost of the process is \$16,640,000. Assuming 6.25 million kg of nitrate are destroyed, the unit cost is \$2.66/kg nitrate.

APPENDIX TABLE 4-2
1992 ORNL NAC ANNUAL COST ESTIMATE

ITEM	1992 COST
Capital costs	20,000,000
Amortized over 20 years	1,000,000/yr
Operating & maintenance	15,640,000/yr (excl. utilities)
Operating labor (4 shifts)	3,375,000/yr
Support labor	640,000/yr
Supplies (excl. aluminum)	425,000/yr
Analytical & HP surveillance	475,000/yr
Utilities	375,000/yr
Aluminum (recycled @ \$0.40/lb)	9,375,000/yr
Maintenance (5% capital/yr)	1,000,000/yr

Source: David Brashears, Martin Marietta Energy Systems

EQUIPMENT

Appendix Table 4-3 lists the major equipment with required sizes for a throughput of about four cubic meters per hour (about one liter per second). Table 4-4 provides descriptions of the major pieces of equipment in the NAC process. Table 4-5 lists the required utilities and process support.

**APPENDIX TABLE 4-3
MAJOR NAC EQUIPMENT LIST**

EQUIPMENT	SIZE	1992 COST, \$	COMMENTS
Feed tank	5,000 gal	50,000	pH adjustment, stir
Reactor vessel	10,000 gal	500,000	Heating/cooling, agitator
Aluminum hopper	1,000 ft ³	100,000	Powder or small shot
Aluminum feeder	5,000 lb/hr	150,000	Screw auger or conveyor
Slurry feed pump	300 gpm	125,000	30 gpm if continuous
Reactor discharge pump	75 gpm	45,000	Sludge pump
Reactor cooler	8,500 kW	500,000	600 ton cooling tower
Sludge Dryer	10,000 lb/hr	150,000	Rotary vacuum dryer
Screw conveyors between dryer and calciner	7,500 lb/hr	100,000	Heated enclosed screw
Calciner	7,500 lb/hr	300,000	400°C, maybe 1,100°C
Ammonia burner	2,500 cfm	80,000	Catalytic burner
Feed mixer	10 hp	10,000	
Piping and valving		500,000	Carbon steel A-53
Structural support	500 tons	750,000	For tanks, pumps, and piping
Feed heater	100 kw	10,000	Electric in-tank heater
NaOH supply system	500 gal/d	250,000	5,000 gal tank
Subtotal--Process Equipment		3,620,000	

Source: David Brashears, Martin Marietta Energy Systems

TABLE 4-4
MAJOR NAC EQUIPMENT AND OTHER DESCRIPTIONS

EQUIPMENT	DESCRIPTION
Feed tank	5,000 gallon with conical bottom, carbon steel coated with epoxy with supports.
Reactor vessel	10,000 gallon capacity: Material of construction: SS 304L Conical bottom Water-cooled jacket cooling load 8,500 kw 3 EA mixer. Assume 20 H.P.
Aluminum hopper Aluminum feeder	Aluminum oxide feeder with screw conveyor and handling equipment.
Slurry feed pump	Moyno slurry pump. 300 gpm. Assume 40' head, assume reactor fill in approximately 11 minutes.
Reactor discharge pump	Moyno slurry pump. 75 gpm.
Reactor cooler	600-ton cooling tower.
Sludge dryer	Rotary vacuum dryer, 110°C. 3' dia. x 4'6" LG 29 CF working capacity.
Screw conveyor	Between dryer and calciner, enclosed and heated, 20 cfm capacity. Carbon steel construction.
Calciner	400°C 2' dia. x 8' LG.
Ammonia burner	Catalytic burner for burning NH ₃ , H ₂ , N ₂ . 2,500 cfm NH ₃ , 250-500 cfm H ₂ . Size unknown.
Feed mixer	10 H.P.
Piping and valving	Assume carbon steel A-53 largest size piping 4" dia.
Structural support	Supports for tanks, pumps, and piping. Allow 500 tons of structural steel.
Feed heater	Electric heater, assume 100 kw submerged inside feed tank.
NaOH supply system	5,000 gal. caustic system with associated pumps, etc.
Transformer	1,000 kw with switch gear, etc.
Air compressor	
NPDES monitoring station	
Isokinetic sampler	For gas discharge stack.
HEPA filtered area	For calciner and solids packaging area. Assume 10,000 CFM.
Building	Pre-engineered building with 40' eave height with diked concrete slab. 30 ton crane, min. heat, exhaust system, office area, change house, etc. 15,000 SF.
Outside utilities/site work	For building.
Dry product handling	Handling equipment for removal of dried material from calciner and other miscellaneous handling equipment.
Process instrumentation and controls	Instrumentation and controls for process, including process control and data acquisition.

Source: David Brashears, Martin Marietta Energy Systems

TABLE 4-5
NAC UTILITIES, SUPPORT EQUIPMENT AND FACILITIES

COMPONENT	SIZE	1992 COST, \$	COMMENTS
1,000 Kw transformer		250,000	With switch gear, etc.
Air compressor		15,000	
NPDES monitoring station		150,000	For pollution monitoring
Isokinetic sampler		150,000	For gas discharge stack
HEPA filtered area	10,000 CFM	300,000	Calciner and solids area
15,000 SF building	40' eave height	2,250,000 (D.B. assumed \$150/ft ² for HLW facility. Use \$75/ft ² for LLW, \$1,125,000)	With 30 ton crane, exhaust, heat office, change house, etc.
Outside utilities/site work		250,000	
Dry product handling		500,000	From calciner, and other miscellaneous equipment
Process instrumentation and controls		400,000	Includes data acquisition
Subtotal—Utilities and Support Equipment		4,265,000	

Source: David Brashears, Martin Marietta Energy Systems

RAW MATERIALS

Aluminum metal is the principal raw material required. Approximately 50 tons per day are consumed. This could be either raw aluminum metal ingot, recycled beverage cans, or contaminated aluminum scrap from various DOE sites. Approximately 500 gallons per day of 50 per cent sodium hydroxide are required. A supply of about 10,000 cubic feet per minute of unconditioned air to the catalytic burner is needed.

UTILITIES

Power consumption is mainly for electrical loads for the pumps, feed tank heating, cooling tower fans and pumps, and agitator drives. Additional heat must be supplied for the product drier and calciner.

CONCLUSIONS

Below are listed conclusions from the 1992 cost estimate for which the assumptions were given above:

- The NAC process is feasible and competitive with other processes for removing nitrates.
- The reactor design is crucial because of the multi-phase exothermic reaction.
- Waste/product streams are readily handled; the hydrogen and ammonia are readily burned to nitrogen and steam and upon calcination. [The report concluded that the aluminum hydroxide should be suitable for land disposal as a refractory alumina, but this is not the case due to leaching, hence the need for sintering or vitrification.]
- Capital cost for this system was estimated to be \$20,200,000 in FY 92 4th QTR dollars.
- Operating cost over the 20-year life of the plant were estimated to be \$2.01-2.66/kg of NO_3 destroyed, 1/3 to 1/2 of 1957 costs quoted for electrolytic and thermal processes. The cost depends on the aluminum requirement with the lower value signifying the stoichiometric aluminum to nitrate ratio and the higher value and the higher value signifying the costs when nitrates are at ppm levels.

Figure 15

Feed Tank 5000 gal Slurry Pump 10,000 gal Capacity

Reactor 10,000 gal Capacity Residence time on cycle time 2 hrs

Sludge Pump

VITRIFICATION

Estimates have been made (Gimple and Diggs) showing the costs of vitrification to be comparable with that of solidification/stabilization. KEI tried unsuccessfully to obtain copies of these estimates despite repeated attempts. Although the cost for making the glass waste form is higher, the total life-cycle costs (including disposal and monitoring for 100 years after disposal) are comparable because of the higher volumes that must be disposed and monitored from grouting.

The direct cost of vitrification was estimated (Gimpel and Diggs, 1992) to be \$1.51/gallon (\$400/m³) and total costs (including disposal) were estimated to be \$3.49-5.52/gallon (\$922-1500/m³).

A 1988 estimate for vitrifying 264,000 tons of waste over 6.5 years determined the following: capital costs, \$24,000,000 (\$91/ton) and operating costs \$73,000,000 for granular glass (\$277/ton) or \$97,000,000 for casting into canisters (\$367/ton).

DEFENSE WASTE PROCESSING FACILITY (SAVANNAH RIVER) BUDGET

According to the FY95 Congressional Budget Request (obtained from Bill Pettigrew, Process Controls Manager for Savannah River), the total project cost (TPC) of the HLW vitrification plant [start date, 4th Qtr. FY79, completion date: 2nd Qtr. FY96 (c)] is \$2,471 million. The net federal total estimated cost (TEC) is \$1,276 million. The DOE escalation rates (% per year) used for this estimate are 3.1 per cent for FY1994 and 3.5 per cent for FY1995.

Table 4-6 presents the federal funds financial schedule. This project previously included funding for incineration facilities to burn slightly radioactive benzene that is a byproduct of the DWPF process. The high-activity precipitate from the salt decontamination process is an organic salt that must be decomposed prior to immobilization in DWPF glass. This decomposition produces slightly radioactive benzene that will be disposed of by incineration. The incineration facilities will be a multipurpose incinerator for liquid and solid hazardous, mixed, and low-level radioactive waste. Funding for the combined incinerator has been redirected from this line item to line item 83-D-184, Non-radioactive Hazardous Waste Management Facilities, to partially fund the multipurpose incinerator.

APPENDIX TABLE 4-6
SAVANNAH RIVER DEFENSE WASTE PROCESSING FACILITY
FINANCIAL SCHEDULE

FISCAL YEAR	APPROPRIATION	ADJUSTMENTS	OBLIGATIONS	COSTS
	(000 Dollars)			
Previous	842,361 d,e	4,623 f	837,738	797,799
1989	92,462 g		92,462	67,946
1990	0		0	47,120
1991	0	101,005	101,005	104,945
1992	18,420 i		18,421	27,619
1993	118,276		118,276	100,084
1994	43,873	19,637 k	63,510	73,755
1995	45,058 l		45,057	55,037
1996	0		0	2,164
TOTAL	1,160,450	125,265	1,276,469	1,276,469

- a Current TEC estimate reflects the current contractor estimate to achieve a simultaneous sludge and precipitate startup on the best possible schedule. A ESAAB is planned for 2nd Qtr. FY94 to revise the cost and schedule baselines.
- b OPC portion of TPC is a management best estimate based on revised current mission guidance (simultaneous sludge and precipitate startup).
- c Construction end date assumes simultaneous sludge and precipitate startup on the best possible schedule.
- d Reflects general reduction of \$1,600,000 in FY86.
- e Reflects reduction of \$1,723,000 for reprogramming of funds for Washington State sales taxes; and \$1,300,000 for management initiative savings.
- f Reflects across the board reduction of 1.66%.
- g Reflects transfer of \$14,800,000 to Project 83-D-148 for the Consolidated Incinerator Facility.
- h FY91 accounting adjustment of \$101,005,278.
- i Includes \$6,597,045 of residual FY91 accounting adjustments and reclassification of \$11,823,578 costs and obligations previously authorized as an operating expense funded project for DWPF post-mechanical completion startup support.
- j Reflects FY93 Amendment of \$32,600,000 and \$27,500,000 FY93 reprogramming. Includes \$58,176,000 for reclassification of costs and obligations previously authorized as an operating expense funded project for DWPF post-mechanical completion startup support.
- k Assumes approval of proposed FY94 reprogramming in the amount of \$19,637,000, which maintains FY96 hot startup schedule.
- l Reflects anticipated amount required to achieve simultaneous sludge and precipitate startup on the best possible schedule.

Source: *FY1995 Congressional Budget Request*, Savannah River Defense Waste Processing Facility, Project No. 81-T-105.

TABLE 4-7
SAVANNAH RIVER DEFENSE WASTE PROCESSING FACILITY
SCHEDULE OF PROJECT FUNDING AND OTHER RELATED
FUNDING REQUIREMENTS

	PREVIOUS YEARS	FY1993	FY1994	FY1995	OUT- YEARS	TOTAL
	(000 Dollars)					
Total facility costs	1,062,394	100,084	73,755	55,037	2,164	1,293,434
Line item—see Table 4-8 (a)	1,045,429	100,084	73,755	55,037	2,164	1,276,469
PE&D	16,965	0	0	0	0	16,965
Operating Exp. funded equip.	0	0	0	0	0	0
Inventories	0	0	0	0	0	0
Other project costs	582,897	178,530	177,423	190,700	47,700	1,177,250
R&D	158,510	27,241	25,229	32,056	5,633	248,669
Conceptual design	0	0	0	0	0	0
D&D	0	0	0	0	0	0
NEPA documen- tation	0	0	0	0	0	0
Other project- related costs	424,387	151,289	152,194	158,644	42,067	928,581
TOTAL PROJECT COST	1,645,291	278,614	251,178	245,737	49,864	2,470,684

a This line item includes cost adjustments addressed in Secretary of Energy Nitrification to Congress dated 9/30/91 and 10/26/92. It also includes the post-mechanical completed startup support (S-4342) that was originally funded as an operating expense funded project (OCP).

Source: *FY1995 Congressional Budget Request*, Savannah River Defense Waste Processing Facility, Project No. 81-T-105.

Table 4-8 presents itemizes the components of the line item, including design and management costs; land and land rights; construction costs; standard equipment; major computer items; removal cost less salvage; design and project liaison, testing, checkout and acceptance; and contingencies.

TABLE 4-8
SAVANNAH RIVER DEFENSE WASTE PROCESSING FACILITY:
DETAILS OF LINE ITEM COST ESTIMATE FROM TABLE 4-7

	ITEM COST	TOTAL COST
	(000 Dollars)	
Design and management costs		681,182
Engineering design and inspection at approxi- mately 57.3% of construction costs, (design, drawings, and specifications)	333,363	
Construction management costs	347,819	
Project management at 0% of construction costs	0	
Land and land rights		0
Construction costs		576,287
Improvements to land	18,000	
Buildings	141,000	
Other structures	36,500	
Utilities	39,000	
Special facilities	341,787	
Standard equipment		5,000
Major computer items		7,000
Removal cost less salvage		0
Design and project liaison, testing checkout, and acceptance		0
Subtotal		1,269,469
Contingencies at approximately 1% of above costs		7,000
Total line-item cost		1,276,469
Non-federal contribution		0
Net federal total estimated cost (TEC)		1,276,469

Source: *FY1995 Congressional Budget Request*, Savannah River Defense Waste Processing Facility, Project No. 81-T-105.

Appendix Table 4-9 presents the annual operating and maintenance costs for the Savannah River Defense Waste Processing Facility.

TABLE 4-9
SAVANNAH RIVER DEFENSE WASTE PROCESSING FACILITY—
RELATED ANNUAL FUNDING

	TOTAL, \$000
Facility operating costs (a)	183,000
Facility maintenance and repair costs	0
Programmatic operating expenses directly related to the facility	0
Capital equipment not related to construction but related to the programmatic effort in the facility (b)	15,000
GPP or other construction related to the programmatic effort in the facility	2,000
Utility costs	0
Other costs	0
TOTAL RELATED ANNUAL FUNDING	200,000

Estimated life of project: 40 years.

- a Includes labor, overhead, utilities and services, process technical support, cold feed chemicals, canister materials, concrete, and miscellaneous supplies for both vitrification and saltstone operations.
- b Average annual replacement costs for melter, vessels, pumps, motors, etc.

Source: *FY1995 Congressional Budget Request*, Savannah River Defense Waste Processing Facility, Project No. 81-T-105.

HANFORD FACILITY

The annual operating costs reported in this section are based upon efficiencies gained by locating the pretreatment, LLW Vitrification Facility, and HLW Vitrification Facility in a central complex (single or multiple facilities using common services).

Pretreatments

According to *Hanford Site Tank Waste Remediation System Technical Strategy* (3/18/94), the pretreatment processes can be designed and constructed for \$650 million (1994 dollars), with annual operating cost of \$90 million.

High-level Processing

According to *Hanford Site Tank Waste Remediation System Technical Strategy* (3/18/94), the HLW Vitrification Facility will cost \$1.5 billion with an annual operating cost of \$150 million.

The allocation for the geologic repository disposal fee is \$2.7 billion. This is based on a single geologic repository and 23,000 m³ of vitrified HLW in 2,300 self-shielded canisters. The interim storage facility for the 2,300 self-shielded 10 m³ HLW canisters consists of a concrete storage pad with an estimated capital cost of \$15 million.

Low-level Processing

According to *Hanford Site Tank Waste Remediation System Technical Strategy* (3/18/94), the LLW Vitrification Facility will cost \$500 million with an annual operating cost of \$90 million (which includes LLW disposal).

HIGH-TEMPERATURE FLUID-WALL REACTOR

TRC prepared a preliminary design and cost estimate report for a one million kilogram-per-year process for denitrification using the high-temperature fluid-wall reactor to treat RFP and SRP wastes. This analysis can be found in Appendix B of *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*.

Four separate scenarios were evaluated for their cost and processing impact in the design. Capital acquisition of major components for the plant based on the most restrictive of the process scenarios was estimated to \$2,170,000. The installed cost was estimated at \$3,725,000 assuming the building and utilities services existed. Overall processing costs including capital debt service, operating and maintenance cost, range from \$1.47/kg to \$2.01/kg for the four scenarios. If debt service is not included and labor, reagent, and electrical costs are reduced, the best case estimate drops to \$0.68/kg.

Processing Scenarios

Four processing scenarios were considered in the process design for the thermal destruction of nitrate wastes. Two process streams, RFP waste nitrate and SRP-Defense Waste Processing Facility wastes were each considered for producing a carbonate product or a

vitreous product. Therefore, the four scenarios were: 1) RFP waste to carbonate, 2) RFP waste to glass, 3) SRP waste to carbonate, and 4) SRP waste to glass. The material flows and chemistry were based on experimental results obtained on pilot studies using a 15.2-cm diameter HTFW reactor in May 1984 at Hercules, CA.

The worst-case scenario was found to be SRP waste to glass, since it represents the maximum power consumption and maximum material handling both on input and output. Plant designs for the other three processing schemes may be derived from the SRP waste-to-glass scheme by deleting functions and substituting the corresponding volume flows of materials. However, processing of waste for all four scenarios can be performed with the same physical equipment, with differing degrees of overall efficiency and different level of unit cost. All four scenarios are summarized in Table 4-10.

TABLE 4-10
PROCESS SUMMARIES FOR HIGH-TEMPERATURE FLUID-WALL REACTOR

	RFP WASTE TO CAR- BONATE	RFP WASTE TO GLASS	SRP WASTE TO CAR- BONATE	SRP WASTE TO GLASS
Inputs:				
Nitrate (kg/yr)	1,000,000	1,000,000	1,000,000	1,000,000
CaO (kg/yr)	0	180,000	0	210,000
SiO ₂ (kg/yr)	0	570,000	0	650,000
Carbon (kg/yr)	310,000	320,000	240,000	250,000
Total feed (kg/yr)	1,310,000	2,070,000	1,240,000	2,110,000
Electrical utility (kWhr/yr)	3,830,000	5,220,000	4,400,000	5,360,000
Outputs:				
Solids (kg/yr)	670,000	1,200,000	880,000	1,400,000
Process gases (m ³ /yr)	570,000	620,000	520,000	580,000
NO _x (kg/yr)	1,000	420	260	20

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

Operating Schemes

Seven operating schemes were investigated and, to be conservative, one was chosen that results in an operating efficiency of 50 per cent. In this scheme, the reactor would be operated 24 hours per day, 5 days per week, for 50 weeks per year. The reactor would be started from a cold start every Monday and allowed to cool completely on Fridays.

Reactor Sizing

The reactor sizing was based on previous experimentation by TRC on simulated RFP and SRP wastes and on TRC experience with other feeds. A feed rate of 0.45 kg/min was demonstrated on nitrate wastes using an 11.4-cm process throat reactor. The reactor capacity scales linearly with the process throat cross-sectional area to 2.7 kg/min in a 27.9-cm throat diameter reactor. TRC has processed similar materials at capacities of 13.5 kg/min. Therefore, the facility design basis was chosen at 8.1 kg/min of total feed including glass-forming additives and carbon in the 27.9-cm (nominal 12-inch diameter) reactor.

Capital Costs

The capital acquisition cost for the major pieces of equipment to process SRP nitrates to glass was estimated at \$2,170,000, including \$1,100,000 for the HTFW reactor itself. The estimated cost includes a complete facility with all operations required for an integrated process: feed material handling, blending, off-gas treatment, residue handling, and reactor power supply.

Construction Costs

A construction cost estimate of 1.5 times the acquisition cost was applied for installation of all equipment except for the high-cost items of reactor, reactor power supply, melt crucible, and control computer, which were estimated at 0.5 times acquisition cost. The total estimated installed cost was \$3,725,000. The total cost assumes that the building and HEPA filtration system exist. The processing area requires approximately 2,200 ft² of floor space. To cool glass monolithic waste forms, approximately 2,000 ft² of floor space would be required as a staging area.

Operating and Maintenance Costs

The range of estimated total annual operating and maintenance costs are shown in Table 4-11 and range from \$0.68/kg to \$2.01/kg of waste feed. Assumptions that were made in determining these costs are itemized in Table 4-12.

TABLE 4-11
ANNUAL OPERATING AND MAINTENANCE COST SUMMARY
EXTREMES FOR HIGH-TEMPERATURE FUEL-WALL REACTOR

	WORST CASE: NITRATES TO GLASS (\$/YR)	BEST CASE: RFP NITRATE TO CARBONATE (\$/YR)
Debt service (20-year payout at 11%)	581,782	-----
Maintenance (5% of equipment)	108,495	108,495
Utilities other than process (\$0.07/kW hr)	44,352	25.344 (\$0.03/kWhr)
Process utilities, reagents, nitrogen, packaging	852,700	334,400
Operating & maintenance labor (3 shifts operator, labor, forklift, 1 shift engineer, maintenance worker)	424,060	212,030 (1/2 of worst case)
Total annual expense	2,011,389	680,269
Cost/kg at 1,000,000 kg/yr	\$2.01/kg	\$0.68/kg

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

TABLE 4-12
FINANCIAL SUMMARIES FOR SIX PROCESS SCENARIOS

COST ITEM	PROCESS SCENARIO					
	R.1	R.1*	R.2	D.1	D.1*	D.2
Waste mix, TPY	1100	1100	1100	1100	1100	1100
Carbon, TPY	342	342	352	265	265	274
Carbon cost, \$/T	600	600	600	600	600	600
Total C cost, \$1000	205.2	205.2	211.2	159.0	159.0	164.4
CaO, TPY	0	0	198	0	0	231
CaO cost, \$/T	110	110	110	110	110	110
Total CaO cost, \$1000	0	0	21.8	0	0	25.4
SiO ₂ , TPY	0	0	623	0	0	717
SiO ₂ cost, \$/T	38	38	38	38	38	38
Total SiO ₂ , \$1000	0	0	23.7	0	0	27.2
N ₂ , MMSCFY	36	36	45	35	35	45
N ₂ cost, \$/MCF	4.00	4.00	4.00	4.00	4.00	4.00
Total N ₂ cost, \$1000	144.0	144.0	180.0	140.0	140.0	180.0
Elect. power, MMKWHY	3.8	3.8	5.2	4.4	4.4	5.4
Elect. Cst., \$/KWH	0.07	0.07	0.07	0.07	0.07	0.07
Total Elect., \$1000	266	266	364	308	308	378
Total prod., TPY	738	738	1316	965	965	1552
# of Drums	4217	1476	2632	5514	1930	3104
Drum cost, \$/ea	25	25	25	25	25	25
Total drum, \$1000	105.4	36.9	65.8	137.9	48.3	77.6
Total pkg., Proc. cost, \$1000	720.6	652.1	866.4	744.9	655.3	852.7
Total pkg., Proc. cost, \$/ton waste	655	593	788	677	596	775

* Fused carbonate

R1: RFP mix to produce powdered carbonate.

R2: RFP mix to produce cast vitreous product.

D1: DWPF mix to produce powdered carbonate.

D2: DWPF mix to produce cast vitreous product.

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP-3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

Note that changing the carbon source and negotiating a lower electrical utility rate has a much greater impact on the costs per ton of waste than a choice of the various scenarios. It may be possible to purchase electric power for as little as \$0.03/KWH in certain parts of the country or in many other parts as a negotiated lower rate for a much larger facility.

The most expensive alternative, nitrate waste to glass, is compared to the least expensive case of RFP waste to carbonate. Costs for both SRP and RFP nitrates processed to glass are very similar. The costs are sensitive to whether debt service, utility costs, carbon reagent costs, and labor requirements are included. Debt service is often not included in cost analysis and was excluded from the best-case assumption. Utility costs were assumed to be \$0.07/kWhr for worst case and \$0.03/kWhr for best case. Carbon reagent was priced at

\$0.66/kg for carbon black in the worst case and at \$0.125/kg for carbon black-petroleum coke mixture in the best case. Worst-case labor estimates were conservatively estimated using dedicated operators, laborers, and forklift drivers for 3 shifts/day and dedicated engineering support and maintenance support for 1 shift/day. In the best case, labor was halved because labor could most likely be shared with neighboring processes since the facility is mostly automated. Lower costs than shown could be realized if the facility was run continually on a 7-day-per-week schedule with increased feedstock because the operating efficiency would increase from 50 to 90 per cent.

JOULE-HEATED GLASS FURNACE

MRC completed an operating-cost estimate for a denitrification furnace based on their experience in processing waste nitrate for the NLLWMP using the joule-heated glass furnace. The data presented in Table 4-13 were derived from operating experience on a pilot-scale furnace that was not optimized for nitrate destruction.

The most significant limitation of the pilot-scale glass furnace for denitrification is the small volume of glass (between the top of the electrodes and the top of the AZS refractory) available to assimilate sodium or potassium constituents. Glass formers such as SiO_2 must be added in the off shifts creating a labor intensive effort with this particular furnace. MRC-Mound researchers have recommended several areas for improvement in an actual production process such as furnace chamber redesign for increased free volume so that SiO_2 can be fed with the waste stream. They also recommend investigating glass composition, electrode materials, glass draining, furnace energy conservation and substituting anhydrous ammonia for the ammonium hydroxide reducing agent.

TABLE 4-13
PILOT-SCALE GLASS FURNACE OPERATING COSTS

RFP NITRATE TO GLASS ^a (\$/DAY)		
Utilities (\$0.04/kWhr)		
Electrode power	6 hr @ 120 kWhr	89.55
	12 hr @ 75 kWhr = 64.80	
Cooling system	20 kWhr	= 19.20
Scrub system	17 kWhr	= 5.10
Drain operation	2.5 kWhr	= 0.45
Reagents		75.38
Glass components		
SiO ₂	340 kg =	14.99
CaO	28 kg =	6.17
MgO	17 kg =	22.49
Ammonium hydroxide	312 kg =	31.71
Operating labor (2 shifts at 1 operator/shift)		241.16
TOTAL DAILY EXPENSE		411.09
Cost/kg at 41 kg/hr of processing, 328 kg/day ^b		

^a Single day operation = 8 hours processing, 16 hours glass preparation, drain, temperature cycling.

^b Operation cost of non-optimized, labor-intensive system.

Source: *Waste Generation Reduction—Nitrates: Comprehensive Report of Denitrification Technologies*, A.J. Johnson et al., Rockwell International-Rocky Flats Plant, RFP- 3899, DOE/TIC-4500 (Rev. 73), UC-70, March 1986.

Capital Cost

The capital acquisition cost for the joule-heated glass furnace was approximately \$100,000. Other support systems such as the wet-scrubbing system and HEPA filtration existed before the glass furnace was installed. Also, no estimate was made for storage bins, feeding equipment, or residue-handling equipment.

Operating Cost

The glass furnace as presently configured could process 100,000 kg annually assuming an 84 per cent operating efficiency (305 days per year). The annual operating expense, exclusive of capital debt service consideration, maintenance supplies, maintenance labor or waste package costs, corresponds to \$125,000/year. The unit cost for waste denitrification of \$1.25/kg is high due to the operational constraints of the furnace.

EPA COST ESTIMATE: DRINKING WATER TREATMENT

The EPA has performed cost estimates on nitrate/nitrite removal from drinking water. Removal rather than destruction results in a nitrate/nitrite-containing waste stream that must be disposed. The Best Available Technologies for nitrate/nitrite removal are ion exchange and reverse osmosis, and electrodialysis reversal (nitrate only). The maximum influent concentration of nitrate that allows the 90 per cent removal required to achieve the maximum concentration limit (MCLG) of 10 mg/L to be attained is 100 mg/L as N. For nitrate the MCLG is 1 mg/L and, with a 90 per cent removal rate, the maximum influent concentration is 10 mg/L.

TOTAL COSTS

The EPA estimates that the total cost (late 1986 dollars) of nitrate and/or nitrite removal via ion exchange for a large system that serves more than a million individuals is 77 cents/1,000 gallons of water treated. For a small system that serves 25 to 100 the cost is 3.40 dollars/1,000 gallons. Reverse osmosis treatment ranges from 1.50 to 5.90 dollars/1,000 gallons.

CAPITAL COSTS

The EPA estimates capital costs for an ion exchange nitrate-removal system to range from \$100,000 for a small system serving 25-100 people to \$340 million for a system that serves more than a million. Reverse osmosis capital costs are estimated to be from \$130,000 to \$1.28 billion.

DISPOSAL COSTS

The EPA estimates disposal costs for ion exchange brines that are discharged to a sanitary sewer to be 2 cents/1,000 gallons of drinking water produced for a 650 million gallon-per-day system that serves more than a million individuals. For a small system serving a population of 25-100 having a flow of 13,000 gallons/day, the disposal cost for brine is estimated to be 93 cents/1,000 gallons.

The EPA estimates disposal costs for reverse osmosis brines that are discharged to a sanitary sewer to be 10 cents/1,000 gallons of drinking water produced for a 650 million gallon-per-day system that serves more than a million individuals. For a small system serving a population of 25-100 having a flow of 13,000 gallons/day, the disposal cost for brine is estimated to be 2.20 dollars/1,000 gallons. If the brine is directly discharged, the cost ranges from 0 to 85 cents/1,000 gallons of drinking water produced.

APPENDIX 5. CROSSWALK SEARCH RESULTS

The results of a search of the Crosswalk database for "nitrates, nitrites" are summarized in Table 7-1.

**TABLE 5-1
CROSSWALK DATABASE SEARCH RESULTS**

IDENTIFICATION	TITLE
PAL001/AL-ALO-UMTRA	UMTRA
PAL003/AL-ITRI-DSITE2	Nitrates in Ground Water
POR024/OR-ORNL-X10-6	Tanks at X-10
POR036/OR-Y-12-GW-1	Ground Water at Y-12
PRF010/RF-RFP-OU-4G	Solar Evaporation Ponds
PRF011/RF-RFP-OU-4S	Solar Evaporation Ponds
PRF017/RF-RFP-OU-9P	Original Process Waste Lines
PRL001/RL-RLO-100-1	100 Area Ground Water
PRL007/RL-RLO-100-6	100 Area Burial Grounds
PRL014/RL-RLO-200-11	200 Area Single-Shell Tanks (SSTs)
PRL015/RL-RLO-200-12	200 Area Cribs/Liquid Disposal Units/Vadose Zone
PRL016/RL-RLO-200-12DUP	200 Area Cribs/Liquid Disposal Units/Vadose Zone
PRL017/RL-RLO-200-13	200 Area Ground Water
PRL021/RL-RLO-200-15DUP2	200 Area Piping
PRL023/RL-RLO-200-17	200 Area Burial Grounds
PRL025/RL-RLO-200-19	200 Area Waste Waters
PRL029/RL-RLO-300-23	300 Area Ground Water
PRL032/RL-RLO-300-26	300 Area Laboratory/Sanitary Sewers
PRL036/RL-RLO-1100-30	1100 Area Ground Water (Horn Rapids Landfill)
PSF010/SF-LEHR-LEHR-G2	Shallow Ground Water
PSF013/SF-LEHR-LEHR-S3	Dog Cage Area
PSR009/SR-SRO-FHASB3	New F&H Seepage Basin Ground Water
PSR010/SR-SRO-FHASB2	New F&H Area Seepage Basins
PSR011/SR-SRO-FHSBSL	New F&H Seepage Basins Process Sewer Lines
PSR012/SR-SRO-HLWTF-GW	F&H Area Tank Farm
PSR023/SR-SRO-GSA	General Separations Area-Ground Water
TAL003/AL111201	Supercritical Water Oxidation R&D for Underground Tanks Integrated Demonstration
TAL015/AL121208	Supercritical Water Oxidation (TSR)
TAL058/AL121212	Pilot Demonstration of Nitric Acid Recycle Distillation
TCH003/CH101104	Field-Deployable Infrared Analyzer for Organic Contaminants
TID017/ID121204	Biological Destruction of Nitrates
TID018A/ID121205	Pad A Treatability Study
TID018B/ID121205	Pad A Treatability Study
TID018C/ID121205	Pad A Treatability Study

TABLE 5-1 (CONT.)
CROSSWALK DATABASE SEARCH RESULTS

IDENTIFICATION	TITLE
TID018D/ID121205	Pad A Treatability Study
TID018E/ID121205	Pad A Treatability Study
TID018F/ID121205	Pad A Treatability Study
TID018G/ID121205	Pad A Treatability Study
TID018H/ID121205	Pad A Treatability Study
TOR016/OR111203	Radioactive Sodium Nitrate Waste Treatment
TRL004/RL311104	R&D for In-situ Treatment
TRL013/RL401204	Treatment Technology for TRU Waste
TRL023A/RL321106	R&D for Contaminant Retrieval & Treatment Technologies
TRL033/RL421102	Decontamination of GW from Arid Site Demo Using Supported Liquid Membranes
TRL044/RL421202	UST Retrieval, Transport & Storage Technology Concepts Development
TRL047/RL401206	Ferrocyanide Detection Using Laser Raman Scattering Spectroscopy
TSF025/SF221203	Salt Splitting/Recycle with Bipolar Electrodialytic Membrane

Source: *Technology Needs Crosswalk Report*, 1st Ed., Chem-Nuclear Geotech, Inc., DOE/ID/12584-117, Jan. 1993.

APPENDIX 6. DOE-DEVELOPED TECHNOLOGY CONTACTS AND REPORT PARTICIPANTS

TABLE 6-1
DOE-DEVELOPED-TECHNOLOGY CONTACTS

PROCESS	CONTACT	SITE	TELEPHONE
Biocatalytic destruction of nitrate and nitrite	David Chaiko	Argonne National Lab.	708-252-4399
	James Helt	Argonne National Lab.	708-252-7335
	Unknown	Non-DOE partner University of Iowa	Unknown
Biological denitrification	Paul Taylor	Oak Ridge National Lab.	615-574-1965
	Tony Malinauskas	Oak Ridge National Lab.	615-576-1092
Calcination	Paul Taylor	Oak Ridge National Lab.	615-574-1965
	Tony Malinauskas	Oak Ridge National Lab.	615-576-1092
Chemical reduction	Paul Taylor	Oak Ridge National Lab.	615-574-1965
	Tony Malinauskas	Oak Ridge National Lab.	615-576-1092
Electrochemical reduction	Paul Taylor	Oak Ridge National Lab.	615-574-1965
	Tony Malinauskas	Oak Ridge National Lab.	615-576-1092
	David Hobbs	Savannah River Laboratory	803-725-2838
	John Steele	Savannah River Laboratory	803-725-1830
	John Bockris	Texas A&M University	Unknown
	Ralph White	University of S. Carolina at Columbia	Unknown
Hydrothermal	Paul Taylor	Oak Ridge National Lab.	615-574-1965
	Tony Malinauskas	Oak Ridge National Lab.	615-576-1092
Microwave solidification	Greg Sprenger	EG&G Rocky Flats	303-966-3159
	Jerry Peterson	EG&G Rocky Flats	303-966-5349
	Joel D. Katz	Los Alamos National Lab.	505-665-1424
	Terry White	Oak Ridge National Lab.	615-574-0983
		Non-DOE	
	Louie Sferrazza	EET	615-671-7800
	Bob Peterson	EET	615-671-7800
NAC/NAG/NAX	Paul Taylor	Oak Ridge National Lab.	615-574-1965
	Tony Malinauskas	Oak Ridge National Lab.	615-576-1092
Steam reforming	J.L. Sprung	Sandia National Lab.	505-844-0234
	D.L. Berry	Sandia National Lab.	505-844-0234
	Unknown	Non-DOE partner Synthetica Technologies, Inc.	Unknown

TABLE 6-1 (CONT.)
DOE-DEVELOPED-TECHNOLOGY CONTACTS

PROCESS	CONTACT	SITE	TELEPHONE
Vitrification	J.J. Lucerna	EG&G Rocky Flats	303-966-5927
	J.L. Peterson	EG&G Rocky Flats	303-966-5349
	Rich Peters	Pacific Northwest Lab.	509-376-4579
	Steven Slate	Pacific Northwest Lab.	509-375-3903
	Denny Bickford	Westinghouse Savannah River	803-725-3737
	J.L. Steele	Westinghouse Savannah River	803-725-1830
		Non-DOE partners	
	Unknown	Clemson University	Unknown
	Unknown	EnVitCo, Inc.	Unknown
	Unknown	Massachusetts Institute of Tech.	Unknown
		Rust Remedial Services (Chem Waste Management, Inc.)	
		StirMelter, Inc.	
Joule-heated Glass Melter	Larry Klinger	EG&G Mound	513-865-3078
	Chris Chapman	Pacific Northwest Laboratory	509-376-6576
	Dennis Bickford	Westinghouse Savannah River	803-725-3737
	Ray Richards	Stir-Melter, Inc.	419-536-8828
	Kenneth Wetmore	Stir-Melter, Inc.	419-661-9500
	Pedro Macedo	Catholic University	202-319-5329
Plasma Arc Furnace	Ray Geimer	SAIC	208-528-2144
Minimum Additive Waste Stabilization (MAWS)	Grace Ordaz	DOE Office of Technology Dev.	301-903-7440
	Ian Pegg	Catholic Univ. of America, VSL	202-319-6700
	Xiangdong Feng	Argonne National Lab.	708-252-7362
	James Mazer	Argonne National Lab.	708-252-9798
		Non-DOE	
	Unknown	GTS Duratek	406-494-7287
	Dan Battleson	MSE, Inc.	

Source: KEI

TABLE 6-2
REPORT PARTICIPANTS

CONTACT	TELEPHONE	DIVISION/ ORGANIZATION	COMMENTS
DEPARTMENT OF ENERGY			
Barns, Steve	716-942-4480	West Valley Nuclear Services	Vitrif. Process Dev. Man
Bates, John	708-252-4385	Argonne	Scientist: glass
Beamon, Gordon	509-376-1000	Hanford	Tech.Dev. Prog. Office
Berry, Jan	615-574-6907	Oak Ridge	MAWS
Bickford, Dennis	803-725-3737	Savannah River	Vitrification
Bloom, Gary	615-241-3827	Oak Ridge, HAZRAP	
Boomer, Kale	509-376-7686	Hanford	Team leader: facility config.
Brashears, David	615-574-3275	Oak Ridge	Cost estimator
Carter, Joe	803-557-2587	Savannah River	Technical
Counce, Pete	615-241-3816	Oak Ridge	Off-gas
Creer, Jim	509-376-5853	Hanford	
Cruse, Jon	509-372-1024	Hanford	Grout cost estimate
Faucet, Andrea	303-966-6420	Rocky Flats Plant	
Francis, Chet	615-574-7257	Oak Ridge	
Higley, Bruce	509-376-5694	Hanford	
Hilton, Donny	803-725-8183	Savannah River	
Hobbs, David	803-725-2836	Savannah River	
Jugan, Mike	615-576-0169	Oak Ridge	Scrap aluminum
Kent, Chris	208-526-3809	Westinghouse WINCO	
Ketola, Steve	716-942-4314	West Valley	Vitrification
Kong, Peter	208-526-7579	Idaho Nat. Engr. Lab	Off-gas
Krumnine, Paul	301-990-3005	Waste Policy Inst.	
Lee, Doug	615-576-2689	Oak Ridge	NAC/NAG/NAX
Mattus, Al	615-576-1795	Oak Ridge	NAC/NAG/NAX
McGinnis, Phil	615-576-6845	Oak Ridge	NAC/NAG/NAX
Peters, Richard	509-376-4579	PNL/Battelle	
Pettigrew, Bill	803-557-1059	Savannah River	Financial controls Mgr.
Quadrille, Marilyn	509-376-4484	Hanford/PNL	Software
Rowley, Lorie	509-373-0651	Hanford	
Sales, Brian	615-576-7646	Oak Ridge	Waste forms
Sams, Terry	615-241-2409	Oak Ridge	Disposal requirements
Sears, Mildred	615-574-6300	Oak Ridge	Waste compositions
Sherick, Mike	208-526-6800	EG&G	EG&G cost model
Shropshire, David	208-526-6800	EG&G Idaho	EG&G cost model
Spence, Roger	615-574-6782	Oak Ridge	
Taylor, Paul	615-574-1965	Oak Ridge	Waste compositions
Tiegs, Terry	615-574-5173	Oak Ridge	NAC/NAG/NAX
Walker, Joe	615-241-4858	Oak Ridge	NAC/NAG/NAX
Williams, Kent	615-574-8156	Oak Ridge	Fast model
Youngblood, Lloyd	615-574-6814	Oak Ridge	NAC/NAG/NAX

**TABLE 6-2 (CONT.)
REPORT PARTICIPANTS**

CONTACT	TELEPHONE	DIVISION/ ORGANIZATION	COMMENTS
ENVIRONMENTAL PROTECTION AGENCY			
Parrotta, Marc	202-260-3035	EPA	Drinking water
PRIVATE INDUSTRY			
Barn-Smith, Peter	505-262-8762	IT—Albuquerque	Cost estimates
Becker, Bruce	702-295-6808	Reynolds Elec. & Eng.	Disposal and transportation costs
Biagi, Chuck	415-442-7740	Morrison Knudson— Environmental	
Bilts, Vicci	615-483-0666	PAI	Disposal costs
Cameron, Rick	509-372-5801	Ensearch	Risk assessment software
Cook, Phillip	215-481-6331	Air Products	Ammonia/NO _x systems
Feizollahi, Fred	415-442-7546	Morrison Knudson— Environmental	EG&G cost modules
Gimpel, Rod	513-648-6113	Fermco	Cost estimates
McGehee, Matthew	615-882-0457	Kendrick Trucking	Transportation costs
Ming, David	215-481-6989	Air Products	Off-gas systems
Peterson, Bob	615-671-7800	EET	Microwave sintering
Teheranian, Ben	415-442-7600	Morrison Knudson— Environmental	EG&G cost modules
Wong, Belenda	415-442-7600	Morrison Knudson— Environmental	EG&G cost modules
Wooley, Frank	607-974-6070	Corning Glass	Glass making
Zuckett, Stephan	907-345-8612	AP Technologies	Biodenitrification
OTHER			
Brandys, Marek	202-319-5549	Catholic University	NO _x treatment
Pegg, Ian	202-319-6700	Catholic University	Vitrification

Source: KEI

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