Integrated Thermal Treatment System Study— Phase 2 Results

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ABSTRACT

This report presents the second phase of a study on thermal treatment technologies. The study consists of a systematic assessment of nineteen thermal treatment alternatives for the contact-handled mixed low-level waste (MLLW) currently stored in the U.S. Department of Energy complex. The treatment alternatives consist of widely varying technologies for safely destroying the hazardous organic components, reducing the volume, and preparing for final disposal of the MLLW. The alternatives considered in Phase 2 were innovative thermal treatments with nine types of primary processing units. Other variations in the study examined the effect of combustion gas, air pollution control system design, and stabilization technology for the treatment residues. The Phase 1 study, the results of which have been published as an interim report, examined ten initial thermal treatment alternatives. The Phase 2 systems were evaluated in essentially the same manner as the Phase 1 systems. The assumptions and methods were the same as for the Phase 1 study.

The quantities, and physical and chemical compositions, of the input waste used in the Phase 2 systems differ from those in the Phase 1 systems, which were based on a preliminary waste input database developed at the onset of the Integrated Thermal Treatment System study. The inventory database used in the Phase 2 study incorporates the latest U.S. Department of Energy information. All systems, both primary treatment systems and subsystem inputs, have now been evaluated using the same waste input (2,927 lb/hr).

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ABBREVIATIONS AND ACRONYMS

APC	air pollution control
ANSI	American National Standards Institute
ASPEN	ASPEN PLUS computer code
BDAT	best demonstrated available technology
BIF	boiler and industrial furnace
CAA	Clean Air Act
CEM	continuous emissions monitoring
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CM	construction management
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRE	destruction removal efficiency
EM-50	Environmental Management Office of Technology Development
EPA	U.S. Environmental Protection Agency
ES&H	environmental, safety, and health
F&ORs	functional and operational requirements
FAR	Federal Acquisition Regulations
FAD	functional allocation diagram
FFCA	Federal Facility Compliance Act of 1992
GOCO	government owned and contractor operated
HEPA	high-efficiency particulate air (filter)
HVAC	heating, ventilation, and air conditioning
IAEA	International Atomic Energy Agency
ICPR	International Commission on Radiological Protection
INEL	Idaho National Engineering Laboratory
ITTS	integrated thermal treatment system
LDR	land disposal restriction
LLNL	Lawrence Livermore National Laboratory

LLW	low-level (radioactive) waste
M&O	management and operations
MEO	mediated electrochemical oxidation
MK	Morrison Knudsen Corporation, Engineering, Construction & Environmental Group
MLLW	mixed low-level (radioactive) waste
mm	million
MSO	molten salt oxidation
MWIR	Mixed Waste Inventory Report
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
NRC	Nuclear Regulatory Commission
OMB	Office Management and Budget
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
O&M	operations and maintenance
PAN	passive/active neutron
PCB	polychlorinated biphenyls
PIC	product of incomplete combustion
PFD	process flow diagram
PLCC	planning life cycle cost
PNL	Pacific Northwest Laboratory
ppmv	parts per million (by) volume
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RTR	real-time radiography
RWMC	Radioactive Waste Management Complex
(s)	solid state
SAIC	Science Applications International Company
SCC	secondary combustion chamber
SCWO	supercritical water oxidation

SEG	Scientific Ecology Group
SGS	segmented gamma scanning
SNR	sorting not required
SR	sorting required
SSL	Scoping Study Layout
TCLP	toxicity characteristic leaching procedure
TD	thermal desorption
TDS	total dissolved solids
TOC	total organic carbon
TRU	transuranic
TSCA	Toxic Substances Control Act
TSD	treatment, storage, and disposal
VOCs	volatile organic compounds
WIPP	Waste Isolation Pilot Plant

Integrated Thermal Treatment System Study— Phase 2 Results

1. INTRODUCTION

1.1 Background

The U.S. Department of Energy's (DOE) Environmental Management Office of Technology Development (EM-50) has commissioned an integrated thermal treatment system (ITTS) study to assess alternative systems for treating contact-handled, alpha and nonalpha, mixed low-level radioactive waste (MLLW). The MLLW in the DOE complex consists of organic and inorganic solids and liquids comprising a wide variety of materials contaminated with radioactive substances. Treatment systems are needed that will destroy the organic material. Other operations are needed to stabilize the treatment residues, inorganic materials, and radionuclides prior to disposal in a MLLW disposal facility. Regulations promulgated by both DOE and the U.S. Environmental Protection Agency (EPA) govern the storage, treatment, and disposal of these wastes.

The purpose of the ITTS study is to conduct a systematic engineering evaluation of a variety of MLLW treatment system alternatives. Preconceptual designs (process flow diagrams, facility layouts, equipment lists, and material mass balances) were developed, and the relative merits and life cycle costs for each were identified. The study further identifies the research and development, demonstration, and testing and evaluation needed to assure unit operability in the most promising system.

In the development of alternatives for this study, information was compiled from a variety of sources. Most often it came from published vendor catalogs for equipment used to form the entire system. In the cases where the central unit operation, e.g., a plasma furnace used for gasification, did not have published catalog data and prices, the appropriate vendors were contacted to obtain information for the preconceptual design of the system. A preliminary copy of this report was provided to each vendor for their comments. The authors have corrected any errors. Some comments suggested different system configurations, but that is beyond the scope of this present study. The identification of a vendor in this study does not constitute an endorsement in any way for a particular product or item of equipment. Nor does the use of a piece of vendor equipment in a system necessarily constitute the vendor's endorsement that such use is the correct or preferred application.

The authors have made every effort to use vendor information correctly and to make accurate representations as to the performance of such equipment within the context of the total system. Most often the assessments are based on engineering judgment and not on actual equipment performance data. Thus, the judgments are subjective. While in no case has there been any willful intent to inaccurately describe the system performance, the opinions stated in this report are not a substitute for valid performance data or trial burns. In addition, since there are a multitude of treatment system combinations, only a few could be evaluated in this scope of work.

The ITTS study was divided into two phases. The Phase 1 report¹ evaluates ten thermal treatment systems based on incineration and plasma destruction.^a Thermal treatment^b is the most effective technique for destroying toxic organic materials. The ten Phase 1 systems are a rotary kiln incinerator with six variations, a fixed hearth controlled-air incinerator, a plasma hearth melter, an indirectly heated pyrolyzer, and a thermal desorber for inorganic residue with a rotary kiln for the combustible waste fraction.

Because incineration is a mature and proven technology, it has generally been the primary choice of industry for destroying hazardous wastes. The technical risks are low and the costs are well established. Proven effectiveness is a critical issue in the commercial sector where investments are provided by stockholders and the investors want a profit. However, in spite of many years of successful experience with incineration, public opposition to incineration exists. As a result, a number of corporations and research organizations, including the DOE, have developed or proposed alternative thermal treatment concepts. This Phase 2 report is an evaluation of nine alternatives to traditional incineration for treating the DOE MLLW.

1.2 Study Contents

Each of the nine alternative systems evaluated include all subsystems necessary to perform waste receiving and inspection, waste treatment, and treated waste certification and shipping. The subsystems are the building blocks of the integrated thermal treatment systems.

Functional and operational requirements were developed for each subsystem. Conceptual designs were developed using the functional and operational requirements as the design basis. Each conceptual design package includes the subsystem layout, equipment list, and a cost estimate. Individual subsystems were then integrated into a single thermal treatment system. The cost of treatment thus developed is added to the estimated transportation and disposal costs to provide the life-cycle cost of each thermal treatment alternative.

The various waste types identified for treatment in this study are described in the DOE Mixed Waste Inventory Report (MWIR).² Using the information contained in the MWIR, a detailed estimate of the physical and chemical composition of the waste was developed for each DOE site. These data were combined to provide an "average" waste composition for the DOE Complex.^{3,c} In addition, Section 3 provides detailed information on the specific composition of the wastes. The

a. As defined by the EPA in 40 CFR 260.10, p. 10, "Incinerator means any enclosed device that (1) uses controlled flame combustion and neither meets the criteria for classification as a boiler, sludge dryer, or carbon regeneration unit, nor is listed as an industrial furnace, or (2) meets the definition of an infrared incinerator or plasma arc incinerator."

b. As defined by the EPA in 40 CFR 260.10, p. 10, "Thermal treatment means the treatment of hazardous waste in a device which uses elevated temperature as the primary means to change the chemical, physical, or biological character or composition of the hazardous waste. Examples of thermal treatment processes are incineration, molten salt, pyrolysis, calcination, wet air oxidation, and microwave discharge."

c. Science Applications International Corp., Waste Management Technology Division, unpublished data, communication from Taryl Huebner to Fred Feizollahi, "Elemental Composition for Each Physical Matrix for the DOE Complex," April 8, 1994.

systems selected for evaluation were required to treat all types of waste stored in the DOE complex. This requirement created the need for several treatment lines to accommodate the range of MLLW encountered.

1.3 Future Studies

The ITTS Study was initiated in 1993, primarily to determine what research and development tasks would be required to support using various mixed waste treatment technologies. Phase 1 of the study focused on reasonably mature unit operations for the treatment system. The study organized information on the relative life-cycle costs, quantities of gaseous effluents, energy requirements, and volumes of solid residues from systems using different core technologies. The approach was found to be valuable for considering technology choices as part of a total system to treat MLLW. Phase 2 was subsequently initiated to evaluate a selection of new and innovative technologies being proposed by various companies or government laboratories for the treatment of MLLW. Phase 2 continued to focus primarily on thermally-based technologies. However, two Phase 2 systems used chemical processes that operate at moderate temperatures.

Phase 3 is now being planned to review additional non-thermal processes on a similar basis as the 19 systems in Phases 1 and 2. The technologies have not yet been selected. However, they will be required to treat the complete cross section of DOE waste using combinations of unit operations, and to incorporate the treatment residues into a final waste form that satisfies both DOE and EPA regulations.

1.4 Technical Approach

A key to successful evaluation of a thermal treatment system is to use an integrated system engineering approach. The systems discussed in this report consist of all facilities, equipment, and methods needed for treating and disposing MLLW currently stored at the DOE Complex. This includes the complete process from waste receiving through characterization, sizing, incineration, and air pollution control to secondary waste residue processing for eventual disposal. Systems such as plasma melters or electric arc furnaces that vitrify waste residues might appear to cost more initially, but they produce less residue volume for disposal. The systems engineering approach provides a uniform basis to compare the merits of widely varying thermal treatment alternatives.

The main focus of the ITTS study is to examine innovative and cost effective treatment systems that minimize the short- and long-term adverse impacts on the worker and public environment, health, and safety. Examples of such designs are subsystems that use contaminated soil for vitrification of process residues or use CO₂ absorbent materials for volume-reduction of process offgas discharged to the atmosphere.

Initially, under Phase 1 of the study, twelve alternative thermal treatment systems were considered. These twelve systems were variations of the incinerator subsystem, the air pollution control (APC) subsystem, and the waste stabilization subsystem. Incinerators considered were rotary kilns and plasma arc, fixed hearth controlled-air, and fluidized bed incinerators. Air pollution control subsystem designs included both wet and dry technologies. Waste stabilization subsystem options included concrete, polymer, and glass-based operations. Many more than twelve alternative systems could be configured. However, even twelve alternative systems evaluated in detail entailed too much scope for the time and resources available.

Consequently, a panel of engineers with diverse experience and technical backgrounds in incineration and stabilization was convened to reduce the number of possible choices. Ten systems were retained (designated in the Phase 1 report as A-1 through A-6, and B through E; see Table 1-1 and Figure 1-1). As in Phase 1, a panel of engineers with diverse experience and technical backgrounds in thermal treatment and waste stabilization was convened to select the systems to be studied in Phase 2. Nine systems were selected, which are shown in Table 1-1 and Figure 1-2. Following the numbering system in the Phase 1 report, these systems are designated A-7, C-2, C-3, F-1, G-1, H-1, J-1, K-1, and L-1. The selection process preserved the ability to evaluate the costs and benefits of parameters, such as one-step processing technologies, including molten metal waste destruction, plasma reactors, steam gasification, and the slagging rotary kiln.

Since the public is often concerned with stack emissions, specific attention was focused on alternative APC unit designs. The intent was to specify a configuration that would provide better emission performance than required to meet current EPA standards.

A second major concern of the public is disposal of hazardous solid residues, especially when radioactive. Under the Resource Conservation and Recovery Act (RCRA), thermal treatment alone will not render the wastes nonhazardous. Under EPA regulations, residues might have to be stabilized before disposal if leachability tests (TCLP) are not met. To ensure RCRA compliance and to provide long-term isolation of residues, baseline concept chosen for primary residue stabilization was vitrification. Vitrification, if done correctly, provides the greatest protection against future environmental releases following disposal and also provides a margin against more stringent future release standards. Vitrification binds the hazardous inorganic residues (mostly metal oxides) and the radioactive contaminants (also metal oxides) into a solid solution of rock-like material. DOE is currently supporting considerable research in the field of waste vitrification to improve the process engineering and understand the physical, chemical, and thermal treatment requirements needed to assure high performance. It is also expected that vitrification of residues may result in disposal cost savings and reduced public apprehension.

Variations in the stabilization process included polymers and cement. Some waste residues, such as salts resulting from the neutralization of acidic combustion gases and volatile incinerator fly ash, were stabilized in a polymer (since at vitrification temperatures [up to 1,600°C] salts will volatilize). Mercury is another example of a material that cannot be vitrified. In this study, amalgamation was presumed to be the best stabilization process for mercury. Amalgamation is listed by the EPA as the best demonstrated available technology (BDAT) for radioactive mercury.

As part of the design process, functional and operational requirements, flowsheets and mass balances, and conceptual equipment layouts were developed for each system. Mass balances were performed to account for all materials treated or used in the processes. All secondary residues were processed in accordance with regulatory requirements, and the final volumes for disposal were estimated. Transportation and disposal cost estimates were applied to the disposal volume of each system as part of the planning life-cycle cost (PLCC) estimate. Simplified system energy balances were conducted to assure that no system was excessively energy intensive. Costs have been estimated assuming the system is a government owned and contractor operated (GOCO) facility.

Table 1-1. Systems included in Phase 1 and Phase 2 of the Integrated Thermal Treatment System study.

System description	Designation
Phase 1	
Rotary kiln with air for combustion and dry/wet APC – baseline system	A-1
Rotary kiln with oxygen for combustion and dry/wet APC	A-2
Rotary kiln with air for combustion and wet APC	A-3
Rotary kiln with oxygen for combustion and CO ₂ retention	A-4
Rotary kiln with air for combustion and polymer stabilization	A-5
Rotary kiln with air for combustion and maximum recycling	A-6
Indirectly heated pyrolyzer with oxygen and dry/wet APC	B-1
Plasma hearth furnace with air and dry/wet APC	C-1
Fixed hearth with oxygen and CO ₂ retention	D-1
Debris desorption and grouting with RK for combustibles	E-1
Phase 2	
Slagging rotary kiln	A-7
Plasma furnace, CO ₂ retention	C-2
Plasma gasification	C-3
Molten salt oxidation	F-1
Molten metal waste destruction	G-1
Steam gasification	H-1
Joule-heated vitrification	J-1
Thermal desorption and mediated electrochemical oxidation	K-1
Thermal desorption and supercritical water oxidation	L-1

Figure 1-1. Ten integrated thermal treatment systems evaluated in Phase 1 of the ITTS study.

Figure 1-2. Nine integrated thermal treatment systems evaluated in Phase 2 of the ITTS study.

1.5 Summary of Regulations and Requirements

This section summarizes the regulatory assumptions and requirements used for developing the preconceptual designs and PLCC estimates for the nine systems. Detailed descriptions of specific regulatory assumptions and cost estimating bases and assumptions are presented in the Phase 1 report, Appendices A and D, respectively.

1.5.1 Overall Regulatory and Permitting Issues

It is assumed that a full environmental impact statement will be needed for the integrated thermal treatment facility. The facility will process all of the RCRA waste stored at DOE installations. The main thermal unit in the integrated thermal treatment facility must also conform to the Toxic Substances Control Act (TSCA). It is assumed that a TSCA permit will be required, which is supplementary to the permits required under the RCRA and the Clean Air Act (CAA). It is assumed that the integrated thermal treatment facility will process only limited quantities of the DOE waste covered by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). (This waste is currently buried but may be retrieved). It is assumed that the thermal units will be permitted in accordance with RCRA regulations for hazardous waste facilities. There are guidelines for thermal processing of solid waste in 40 CFR 240 that apply to all systems. There are other RCRA permitting regulations pertaining to particular systems that depend on the type of thermal treatment process used by the system. It is assumed that listed waste will be treated by the thermal treatment facility. Characteristic waste should be pretreated, if necessary, and then treated by an appropriate subsystem. Regardless of whether the waste is listed or not, the generator must determine whether it exhibits any of the four characteristics of hazardous waste by either (1) testing the waste, or (2) applying process engineering knowledge. Management of secondary waste will be in accordance with the EPA "derived from" rule. In this study, it is assumed that residue from treatment of all waste is stabilized to meet the concentration-based extraction test.^d Some of the secondary waste streams in this study are being investigated for potential delisting.

1.5.2 Department of Energy Requirements

The following DOE policies apply to design, construction, and/or operation of each of the nineteen thermal treatment systems. The directives of these referenced policies will need to be considered during any preliminary engineering for treatment systems selected for further consideration. The magnitude of the compliance review activities will be related to how many systems are selected for further comparative analysis. Some of the following requirements focus primarily on a particular activity, e.g., hazardous materials transportation. Design efforts must accommodate procedures identified by these policies.

In addition to DOE policies, guidelines from other government agencies, particularly EPA, must also be reviewed to meet various permitting requirements. The EPA Guidance Document entitled *Quality Assurance and Quality Control for Waste Containment Facilities*, September 1993, is an example of such a guideline. Regulatory guidance for selected technologies may be dependant on the results of development efforts. For example, disposal permitting will require information on the final waste form, using preliminary information on waste products developed from pilot tests or demonstration projects.

d. Toxic characteristic leaching procedure (TCLP)

The following DOE orders and their referenced requirements appear applicable at this time to all systems:

1. Quality Assurance, DOE Order 5700.6C

Quality Assurance requirements have been established to ensure that risks and environmental impacts are minimized and that safety, reliability, and performance criteria are met. The DOE requires that management develop and implement a Quality Assurance program, maintain trained and qualified personnel, and provide a program to assess performance. The program is to detect, prevent, and correct quality problems, and maintain documents and records to ensure compliance with DOE requirements. There are approximately seven additional DOE orders that affect the quality assurance requirements as well as three American Society of Mechanical Engineers standards, one International Atomic Energy Agency (IAEA) standard, one International Organization for Standardization Guideline, five EPA guidance documents, and an American Society for Testing and Materials standard.

2. Occurrence Reporting and Processing of Operations Information, DOE Order 5000.3B

An Occurrence Reporting System has been developed to keep the DOE and DOE contractor line management fully informed about events that adversely affect the environment, the ability of the facility to achieve its intended purpose, or the health and safety of the general public and facility workers. The system consists of procedures for identifying, analyzing, and reporting all "Reportable Occurrences," evaluating and implementing corrective actions, preparing reports to prevent similar occurrences, and maintaining a database of unclassified reports. There are approximately thirteen additional DOE orders that affect the Occurrence Reporting System.

3. Conduct of Operations Requirements for DOE Facilities, DOE Order 5480.19

It is required that DOE facilities be organized, managed, and operated in a manner to assure an acceptable level of safety. Operators of facilities are required to have procedures in place to control the conduct of operations; these procedures are to be consistently reviewed for effectiveness. These procedures include, but are not limited to, operations organization, shift routines and operating practices, control area activities, communications, control of on-shift training, investigation of abnormal events, notifications, control of equipment and systems status, lockouts and tagouts, independent verification, log keeping, operations turnover, operations aspects of facility chemistry and unique processes, operations procedures, and equipment and pipeline labeling.

4. Hazardous Material Packaging for Transport — Administrative Procedures, DOE Order 15402

Procedures have been established by the DOE to ensure that all packaging approved for use in transporting radioactive and other hazardous materials meets all applicable safety requirements. These procedures cover DOE Certificates of Compliance, U.S. Department of Transportation (DOT) exemptions, DOE alternatives, Nuclear Regulatory Commission (NRC) Certificates of Compliance, IAEA Certificates of Competent Authority, DOT specification 7A Packaging Certification, DOT Type B Specification Packaging, Special form certification, and other hazardous materials packaging, explosives classifications, and

rule-making requests. This order also includes the procedures to review DOE safety evaluations and certificates of compliance. There are approximately sixteen additional orders, regulations, and procedures that affect the hazardous materials packaging promulgated by various agencies, including the DOE, DOT, DOD, IAEA, and the International Air Transport Association.

5. Value Engineering, DOE Order 4010.1A

Value Engineering programs have been established to reduce nonessential costs and to improve productivity. In creating a value engineering program, management must establish criteria and guidelines, provide funding for value engineering activities, train personnel in its use, and perform value engineering studies. There are approximately six additional orders and policies that affect value engineering from the DOE, Office of Management and Budget (OMB), Federal Acquisition Regulations (FAR), and the Office of Federal Procurement Policy.

6. Maintenance Management Program, DOE Order 4330.4A

Maintenance activities at DOE facilities are required to promote operational safety, worker health, environmental protection and compliance, property preservation, and cost effectiveness. Safety-critical structures, components, and systems (active and passive) must have a maintenance program to ensure that they meet their design requirements. Periodic inspections must be conducted to assess safety. There are approximately twelve additional DOE orders that affect the Maintenance Management Program.

7. Project Management System, DOE Order 41700.1

The Project Management System has been developed to provide a systematic and coordinated approach to project management that results in efficient planning, management, review, and control of DOE projects. There are approximately 45 additional DOE orders, OMB circulars, FAR regulations, and other public laws that affect the Project Management System.

8. General Environmental Protection Program, DOE Order 5400.1

DOE policy is to conduct its operations in compliance with all applicable environmental statutes, regulations, and standards. The DOE will actively oversee contractors' activities to assure compliance with this policy. There are approximately 13 additional DOE orders that affect the General Environmental Protection Program as well as 22 pieces of Supreme Court legislation, four executive orders, various state and local legislative requirements, and DOE Amended Guidelines on the National Environmental Policy Act (NEPA).

9. Hazardous and Radioactive Mixed Waste Program, DOE Order 5400.3

This guidance is specific to this Oak Ridge Operations Office, and could apply, depending upon the location(s) of the integrated thermal treatment system(s).

10. Environment, Safety & Health (ES&H) Program for DOE Operations, DOE Order 5480.13

The ES&H Program has been adopted by the DOE to assure the protection of the environment and the health and safety of the public, to provide a safe workplace for employees, to protect government property, to assure compliance with applicable statutory requirements affecting federal facilities and operations, to assure quality, and to require line management to be responsible for effective ES&H performance in their programs. There are approximately 16 additional DOE orders and several executive orders that affect the ES&H Program.

11. Environmental Protection, Safety, and Health Protection Standards, DOE Order 5480.4

This order specifies requirements for the application of the mandatory ES&H standards applicable to all DOE contractor operations. It also provides a listing of these standards and identifies their sources. There are approximately six additional DOE orders, one public law, and eight primary Title 29 Occupational Safety and Health Administration (OSHA) regulation sections, as well as many additional executive orders and other agency requirements that affect the ES&H Protection Standards.

12. Fire Protection, DOE Order 5480.7A

The DOE has enacted fire protection standards to minimize the potential for a fire. This order ensures that a fire will not cause a release of radiological or hazardous material that will threaten the environment or public health and safety; that DOE employees, contractor employees, and the general public will be protected from the effects of a fire at a DOE facility; that process control and safety systems are not damaged; that vital DOE programs will not suffer unacceptable delays as a result of fire; and that property damage from fire does not exceed an acceptable level. There are approximately eight mandatory fire protection regulations published by the National Fire Protection Association (NFPA), the DOE, and the Code of Federal Regulations (CFR). There are also 14 reference criteria that pertain to the DOE fire protection program. This order will dramatically affect any treatment system designs.

13. Radiation Protection for Occupational Workers, DOE Order 5480.11

It is DOE policy that facility operations are performed so that radiation exposures are maintained within the limits set by this order. The radiation protection standards are consistent with guidelines from the EPA, National Council on Radiation Protection and Measurements (NCRP), and the International Commission on Radiological Protection (ICRP). There are approximately 17 additional DOE orders that affect the Radiation Protection for Occupational Workers order, and numerous references to the Nuclear Energy Agency, the NCRP, the ICRP, the EPA, and the American National Standards Institute (ANSI). The radiation limits in the reference material are subject to change.

14. Planning and Preparedness for Operational Emergencies, DOE Order 5500.2A

The DOE policy regarding emergency planning would apply during both construction and operations. The selected design of the thermal treatment process and the location of the potential construction will require site-specific considerations for these plans. References similar in magnitude to those required for the earlier identified Fire Protection Order will

need to be applied to selected treatment systems and subsystems. Superfund Amendments and Reauthorization Act Title III and community notification procedures will apply. RCRA location standards, where applied, may reduce some regulatory burden.

15. Work Authorization System, DOE Order 5700.7C

It is DOE policy to establish a work authorization and control process for work performed by designated management and operating contractors. There are approximately nine additional DOE orders that affect the Work Authorization System.

16. Radioactive Waste Management, DOE Order 5820.2A

This DOE document establishes requirements for managing radioactive and mixed waste, and contaminated facilities. Over 50 DOE requirements and laws are attached to determine compliance. This document alone will take extensive analysis to determine whether the designed facility will comply with all applicable federal, state, and local environmental, safety, and health laws and DOE requirements. Chapter 3, *Management of Low-Level Waste*, and Chapter 6, *Waste Management Plan Outline*, are relevant to construction design and operation requirements.

17. General Design Criteria, DOE Order 6430.1A

The DOE has adopted hundreds of pages of General Design Criteria to guide the acquisition of the department's facilities and to establish responsibility and authority for the development and maintenance of these facilities. The criteria require that architectural and engineering principles be applied to the planning, design, construction, and alteration of DOE facilities, including the incorporation of energy conservation. All planning, design, and construction of facilities will be performed in a manner that will satisfy all applicable Executive Orders, Federal laws, and regulations. All facilities will be designed and constructed to be reasonable and adequate for their intended purpose and consistent with health, safety, security, and environmental protection requirements. Numerous references will need to be reviewed for current applicability.

1.5.3 Primary EPA Requirements

1.5.3.1 Clean Air Act Considerations. The CAA requires that all source categories, including thermal treatment units, be identified, and that technology-based emission standards be promulgated for each category. Tables 1-2 and 1-3 provide emission limits for nonmetals and metals, respectively, for ITTS design. Details regarding the bases for selecting these limits are discussed in Appendix A of the Phase 1 report.

1.5.3.2 Overall RCRA Considerations. RCRA permitting regulations for incinerators apply to the baseline system, System A-1 (rotary kiln, air), and to System A-7 (slagging rotary kiln). These units will be permitted in accordance with 40 CFR 270.62. This regulation requires three things: (1) a description of conditions necessary to operate in compliance with performance standards of 40 CFR 264.343 during the permit period, (2) a description of restrictions on waste constituents, waste feed rates, and operating

Table 1-2. Proposed emission limits for nonmetals.

Pollutant	Regulatory limit	Averaging period of emission limit	Proposed level to be used by ITTS working group
Carbon monoxide (CO)	100 parts per million by volume (ppmv) from thermal treatment unit		100 ppmv from thermal treatment unit
	35 ppmv from stack	1 hour	35 ppmv from stack (1 hr period)
	9 ppmv from stack	8 hour	9 ppmv from stack (8 hr period)
Total hydrocarbons	20 ppmv		20 ppmv
Sulfur dioxide	100 micrograms/cubic meter ($\mu\text{g}/\text{m}^3$)	1 year	100 $\mu\text{g}/\text{m}^3$
Ozone	235 $\mu\text{g}/\text{m}^3$	1 hour	235 $\mu\text{g}/\text{m}^3$
Particles smaller than 10 μm	34 milligrams/cubic meter (mg/m^3)		34 mg/m^3
Sulfur dioxide	80 $\mu\text{g}/\text{m}^3$ 365 $\mu\text{g}/\text{m}^3$ 1,300 $\mu\text{g}/\text{m}^3$	1 year 24 hours 3 hours	365 nanograms/cubic meter (ng/m^3) (24 hr period)
Polychlorinated biphenyls (PCB)	destruction removal efficiency (DRE) of 99.9999%		DRE of 99.9999%
Radionuclides	10 millirems/year (mrem/yr)	1 year	10 mrem/yr
Principal organic hazardous constituent (POHCs)	DRE of 99.99%		DRE of 99.999%
Dioxins	30 ng/m^3		0.1 ng/m^3
HCl	1.8 kilograms/hour (kg/hr)	1 hour	1.8 kg/hr
Chlorine (Cl_2)	0.001 gram/second (g/s)		0.001 g/s
Radon 222	3×10^{-9} microcurie/milliliter ($\mu\text{Ci}/\text{ml}$)	1 year	3×10^{-9} $\mu\text{Ci}/\text{ml}$

Table 1-3. Proposed emission limits for metals.

Pollutant	EPA limit	Averaging period of emission limit	Proposed level to be used by ITTS working group (g/s averaged over 1 hour)
Antimony	0.061 g/s	1 hour	0.0061
Barium	10.0 g/s	1 hour	1.0
Nickel	0.0084 g/s	1 hour	0.00084
Mercury	0.016 g/s	1 hour	0.0016
Selenium	0.80 g/s	1 hour	0.080
Silver	0.61 g/s	1 hour	0.061
Arsenic	0.00047 g/s	1 hour	0.0000471
Thallium chlorides	0.061 g/s	1 hour	0.0061
Cadmium	0.00111 g/s	1 hour	0.000111
Lead	0.0177 g/s 1.5 µg/m ³	1 hour annual	0.00177
Beryllium	0.000833 g/s 0.0001155 g/s	1 hour 24 hours	0.00008333
Chromium	0.0001666 g/s	1 hour	0.0000166

parameters as described in 40 CFR 264.345, and (3) a proposal for a trial burn. RCRA monitoring requirements must be undertaken while thermally treating hazardous waste.

Thermal treatment processes that do not use a flame and that are methane-reforming processes would be classified as either miscellaneous thermal units or as industrial furnaces. Since the definitions of miscellaneous thermal units and industrial furnaces are given in 40 CFR 260.10, the permitting regulations for boilers and industrial furnaces (BIFs) (in 40 CFR 266 Subpart H) would apply. These regulations would apply to Systems C-3 (plasma gasification), F-1 (molten salt oxidation), G-1 (molten metal waste destruction), and H-1 (steam gasification) if, in fact, these systems were considered methane-reforming industrial furnaces.

Systems K-1 (thermal desorption and mediated electrochemical oxidation) and L-1 (thermal desorption and supercritical water oxidation) do not qualify as recycling facilities, incinerators, or boilers and industrial furnaces. Therefore, they fall into the class of miscellaneous facilities with regard to RCRA permitting. With the exception of the slagging rotary kiln, all other systems might also qualify as miscellaneous facilities. Permitting requirements in 40 CFR 270.23 would apply.

System G-1 (molten metal waste destruction) might not require RCRA facility permitting at all, depending on whether the permitting agency classifies it as a recycling facility or a thermal waste treatment facility. A system will be classified as a recycling facility if a high enough percentage of the output consists of products with legitimate markets. There are no RCRA permitting regulations

for recycling facilities. If not considered a recycling facility, System G-1 would probably fall into the miscellaneous class, discussed above. According to the manufacturer, Molten Metal Technology, a facility using the catalytic extraction process and fed a certain waste feed was licensed in Massachusetts as a recycling facility rather than a waste treatment facility. Ohio has issued a similar written determination, and the manufacturer expects similar results from discussions with Texas and Tennessee regulators. However, none of these facilities are designed for operation using radioactive waste. In the authors' opinion, radioactive residues will not be recyclable for unrestricted use.

1.5.3.3 Waste characterization. Each step of the thermal treatment process will require waste characterization, starting with the individual waste containers and ending with the final waste form, offgas, and scrubber solids. Current drum assay procedures for radionuclides can have errors of $\pm 100\%$ at the threshold level of 100 nanocuries per gram (nCi/g) between transuranic (TRU) waste and low-level waste (LLW). This accuracy should be adequate for characterizing input fed to a thermal treatment unit. There are no EPA requirements on radionuclides related to nondestructive assaying.

X-ray radiography can be useful in presorting waste before processing. Throughout normal operation, the owner/operator of a thermal treatment unit must conduct a waste analysis adequate to verify that waste fed to the unit is within the physical and chemical limits specified in the permit. Existing EPA SW-846 analytical methods will be used for analyzing scrubber solutions. Radioassay of the TRU content of bottom ash and fly ash will be performed by routine methods. Scrubber salt residues will be analyzed for salt content to reach a decision on how to formulate for conversion to the final waste form. Analysis for RCRA metals will not be needed since it can be assumed that the waste will have levels of regulatory concern. Analysis for total carbon is required to show the absence of organics. If carbon is present in significant quantities, further analyses for organic compounds could be required (e.g., thermal desorption/gas chromatography mass spectrometry). According to an EPA requirement, an analysis of the final waste form for toxics in accordance with the TCLP will take place to show that the treatment to create a final waste form is effective in reducing the level to that acceptable for burial in a mixed waste facility.

Input waste: physical and chemical characteristics. The ITTS will treat the waste types described in Table 1-4. The nominal capacities of the subsystems are assumed to be as shown in this table. Table 1-5 shows the waste input rates to ITTS subsystems. The input waste assumed in the ITTS study is contact-handled mixed radioactive waste (as defined in Reference 2), including alpha-contaminated MLLW, which contains a variety of anticipated hazardous materials. It is assumed that the input waste contains EPA-listed hazardous organics or other RCRA-controlled substances and characteristic waste. The treatment system receives incoming solid and sludge waste in drums, metal bins, and wooden or fiberglass boxes shipped to the treatment facility.

Input waste: radiological characteristics. Input waste will be alpha and nonalpha MLLW. Alpha low-level waste has more than 10 nCi/g of TRU but less than 100 nCi/g. All waste considered in the ITTS study is contact-handled waste. If high-activity waste inside shielded containers is found, it will be rejected and returned to its point of origin. Consequently, the system will be designed with minimum shielding. Some shielding could be necessary in areas of the facility with concentrated TRU waste or fission-product radionuclides (e.g., thermal treatment ash). However, shielding is not considered to be a factor in the relative performance of the different systems. No attempt has been made in this study to provide for shielding in any unit operation.

Table 1-4. DOE total system input MLLW.^a

Type of waste	Total quantity (lb)	Mass feed rate ^b (lb/hr)	Nominal capacity ^c
Metal with surface contamination	37,777,699	468	200 lb/hr
Metal with fixed contamination	11,994,026	149	100 lb/hr
Combustible solids, liquid, and debris	82,122,116	660	660 lb/hr
Noncombustible solids, liquid, and debris	166,573,443	1,340	1,340 lb/hr
Lead with surface contamination	4,514,307	5	60 lb/hr
Lead with entrained contamination	18,960,089	21	250 lb/hr
Aqueous waste ^d	8,183,758	80	20 gpm
Mercury contaminated waste	2,574,148	50	100 lb/hr
Special waste	11,748,963	153	150 lb/hr
Sulfate and halide salts	119,870	1	e
Empty drums	f	f	f
Empty bins	g	g	g
Total	344,568,419	2,927	—

a. Compositional percentage breakdowns from Reference 3, Vol. 1, Table 2.2, and Text Footnote c.

b. Feed rates are calculated based on having one integrated thermal treatment facility operating 4,032 hours per year for 20 years.

c. Nominal capacities are based on smallest available equipment and also account for secondary work.

d. Solar pond waste at Rocky Flats Plant (approximately 101,752,000 lbs) has been deleted as a feed to an integrated treatment facility. It is assumed that the pond waste will be treated at Rocky Flats Plant by a system specially designed for this waste stream.

e. The capacity for polymer stabilization depends on system requirements.

f. Assume 50% of drums (11,084,014 lb) to metal melting and 50% (11,084,014 lb) to metal-with-surface-contamination stream.

g. Assume all bins are fiber-reinforced plastic (4,677,120 lb/hr) and are classified as combustible solids. Hence, this input is added to the combustible solids and debris category above.

1.5.3.4 Waste Treatment.

Pretreatment. Waste pretreatment will be compatible with the requirements of the primary waste treatment technology. For example, bulk metal (e.g., ferrous metal and lead objects larger than about 10 cm) will be removed from the waste stream and sent to the appropriate treatment subsystem. Containers of potentially temperature-sensitive materials, such as pressurized gas cylinders, will be set aside and safely depressurized, emptied, or otherwise made safe for the next step of treatment.

Table 1-5. Waste input rate to treatment subsystems.

Waste Type	Treated by Subsystem	Mass Input Rate (lb/hr)
Main Thermal Treatment Subsystems:		
Combustible Waste	Main Thermal Treatment	660
Noncombustible Waste	Main Thermal Treatment	1,340
Auxiliary Subsystems:		
Metallic Waste (Surface Contamination)	Metal Melting	149
Metallic Waste (Entrained Contamination)	Metal Decontamination	468
Lead	Lead Recovery	26
Mercury Contaminated Waste	Mercury Amalgamation	50
Aqueous Waste	Aqueous Waste Treatment	80
Special Waste	Special Waste Treatment	153
Halide and Sulfate Salts	Polymer Stabilization	1
Soil Additive	Main Thermal Treatment	Depends on main thermal treatment, usually 370 to 560 lb/hr
Total	All Subsystems	2,927 plus soil

Note: Waste input mass flow rates do not include secondary wastes generated by treatment subsystems.

Primary treatment. Combustible materials will be either oxidized or thermally decomposed in a chemically reducing environment to achieve volume reduction and destruction of RCRA-controlled materials. Noncombustible materials, such as inorganic sludge contaminated with chlorinated solvent, will be treated to destroy RCRA-controlled contaminants, if present, and to remove moisture before stabilization. Levels of substances in the offgas from primary treatment will meet requirements set forth in RCRA, TSCA, and other regulations on air pollution. Temperatures and times of thermal treatment may differ from those set forth by the EPA, provided that process experience can demonstrate that the effluent meets RCRA and TSCA destruction efficiency requirements. These requirements will be met while keeping waste stream characterization to a minimum. Parts of the system that process alpha-contaminated MLLW will operate at slightly negative pressure to avoid

releasing contamination outside the units. Tolerable in-leakage will be provided for in the design requirements. For systems using air for combustion, the air supply will be taken from the innermost containment.

Metals processing. Bulk ferrous metals will be treated either by decontamination to free-release standards of DOE Order 5400.5 or by metal melting to assure destruction of any RCRA-controlled contaminants and removal of surface contamination by slagging. Metal treated by melting will be removed from the disposal stream and be considered recyclable for DOE purposes with zero economic value. The metal is assumed to be recyclable for uses such as shielding and containers for radioactive material. Thus, no cost for disposal is incurred. Some of the Phase 2 systems with one-step processing eliminate the need for a separate metal melting subsystem.

Lead recovery. Bulk lead, such as lead brick, will be treated by surface decontamination if it is reasonably determined to have no activation products. Other lead, such as blankets, wool, and activated lead, will be treated by melting to remove combustible nonlead products and will be cast into blocks for reuse by DOE. Consequently, no cost for disposal is assumed. The alternative to reuse will be treatment to EPA microencapsulation standards.

Mercury separation. Elemental mercury, if found to have radioactive contamination, will be treated by amalgamation. If not radioactive, elemental mercury will be recovered by distillation, captured, and released for recycling.

Secondary treatment. No liquid effluent will be generated. More precisely, the facility will not discharge liquid effluent, though some water vapor will be discharged by way of building exhaust and the process stack.

Air pollution control systems will meet or exceed current and anticipated regulations. Performance specifications will be set to meet or exceed current regulations by one order-of-magnitude (10 times) for metals and organics.

Aqueous waste will be treated to evaporate water and immobilize the contaminants into the final waste forms. Highly acidic or alkaline aqueous waste will be pretreated to return the pH to near neutral. Organic liquid waste will be treated by oxidation. Two Phase 2 treatment systems, supercritical water oxidation and mediated electrochemical oxidation, will be used to treat organic liquid waste. If chloride salts are formed, these will be treated in a similar manner as salt residues from offgas treatment.

1.5.3.5 Waste Output.

Output waste form. The characteristics of the system's primary and secondary waste output will meet current and anticipated disposal regulations, such as 40 CFR 268, for substances regulated by RCRA and DOE Order 5820.2A. The desired output waste form is a stable, leach-resistant, high-integrity solid produced by one of two processes: vitrification or solidification. Final waste forms for LLW will be delistable to reduce the cost of disposal (Subtitle D versus Subtitle C) and meet the requirements of DOE 5820.2A for LLW. If the waste qualifies as TRU waste, then the final waste forms will comply with Waste Isolation Pilot Plant (WIPP) waste acceptance criteria, DOE's TRUPACT II packaging and shipping criteria, and packaging criteria required by 10 CFR 71. The potential for gas generation will be minimized. If this requirement results in a significant increase in the final waste volume, it will be reconsidered. If the waste is alpha MLLW, the final waste form

will be able to satisfy performance assessment requirements for each site for alpha concentrations up to 99 nCi/g TRU materials.

Disposal. Shallow land burial is the assumed disposal option for LLW and treated MLLW. Engineered shallow land disposal is the assumed disposal option for alpha LLW and alpha MLLW. For this study, costs for engineered disposal facilities have been used.

For purposes of calculating transportation and disposal costs, it is assumed that the output LLW, MLLW, alpha LLW, and alpha MLLW will be shipped to the Nevada Test Site for disposal. However, for purposes of selecting an output waste form, it is assumed that the Nevada Test Site might not be available; therefore, the final waste form will be stable so that it can be accepted at surface disposal facilities at other major DOE installations, including Hanford Site, Washington; Idaho National Engineering Laboratory, Idaho; Oak Ridge Reservation, Tennessee; Los Alamos National Laboratory, New Mexico; and Savannah River Site, South Carolina.

All wastes from other sites will be transported to one of these sites for disposal. An average cost of disposal will be used for all shipments.

Packaging. The output waste will be packaged in 55-gallon drums meeting DOT requirements. For vitrified waste, thick-walled steel or other appropriate containers will be required if the casting process involves pouring molten materials directly into the waste container. It is assumed that these containers can be qualified to meet DOT and TRUPACT II criteria or equivalent. Final waste forms will meet contact handling requirements with no additional shielding other than the shipping container.

1.5.3.6 Operation and Design Considerations.

Facility design. Facilities handling MLLW are placed in Seismic Category 1. Buildings that handle MLLW are classified as moderate-hazard facilities.⁴ The facilities will be designed in accordance with applicable local, state, and federal regulations, including general design criteria for DOE facilities contained in DOE Order 6430.1. In particular, RCRA places design constraints on storage and treatment facilities and places performance specifications on the waste stabilization. The facility's units will be designed to handle at least 125% of the expected mass flow rates, shown on process flow diagrams (PFDs) for each system.

To ensure the safety of personnel, the system for treating alpha LLW and alpha MLLW should be designed to accommodate TRU waste with radioactive levels exceeding 100 nCi/g. The primary design requirement is triple containment of alpha contamination.

Since the treatment systems are used for alpha and nonalpha waste, they will have a tertiary containment system for all process steps from waste sorting through waste stabilization. Only two levels of containment are required for other processes involving materials with a limited potential for becoming airborne.

Technology maturity. Acceptable technologies are those that have successfully completed the proof-of-principal phase or those that have successful operating experience in other industrial applications. Technologies must be ready for pilot-scale demonstration in 2 years, incorporation into a final design in 3 years, and construction in 5 years. Some of the innovative systems evaluated in Phase 2 may not meet this criteria.

Operating conditions. The preconceptual designs will be based on the assumption that MLLW inventories will be processed in treatment facilities, placed in storage facilities, and disposed of during a 20-year operating period. During this period, the treatment facility will operate 24 hours per day, 5 days per week, 240 days per year, at 70% of capacity during operation. This is equivalent to operating 4,032 hours per year of operation. In unit operations with small capacities, where a three-shift operation is not justified, a single shift per day or part-time shifts are assumed.

1.6 Phase 2 ITTS Study Team

The overall project was initiated and directed by Carl Cooley, of the DOE, EM-50. A team of employees of Lockheed Idaho Technologies Company (LITCO) and Morrison Knudsen Corporation, Engineering, Construction & Environmental Group (MK) performed the engineering and analysis for the ITTS study. In addition to the authors, the following individuals and organizations furnished their expertise and services for the ITTS study.

2. SYSTEMS TECHNOLOGIES

Nine distinct thermal treatment systems were examined by the Phase 2 study; these systems are listed in Figure 1-2. System A-7 uses a slagging rotary kiln. Systems C-2 and C-3 use a plasma furnace. System F-1 uses molten salt oxidation (MSO). System G-1 involves molten metal waste destruction. System H-1 uses steam gasification. System J-1 uses joule-heated vitrification. System K-1 involves thermal desorption and mediated electrochemical oxidation (MEO). System L-1 uses thermal desorption and supercritical water oxidation (SCWO). In addition, the baseline system presented in the Phase 1 report, System A-1 (Rotary kiln, air), is also described in this report for reference; a perspective view of the major components of System A-1 is shown in Figure 2-1.

Each system consists of several subsystems, which are listed in Table 2-1. Whenever possible, Table 2-1 compares the subsystems with those of the baseline system (A-1). The baseline system uses conventional technology, employing a rotary kiln incinerator as the main thermal treatment unit, an APC subsystem based on dry filtration followed by wet scrubbing, and a melter for ash solidification. Table 2-1 indicates whether a given subsystem is the same as that contained in the baseline system or is whether it is a different concept. For brevity, whenever a subsystem is similar to the baseline system, the reader is referred to the descriptions provided in the baseline system discussion. Only subsystems that use new concepts are discussed for the Phase 2 systems.

Systems described in this section were developed based on the requirements and assumptions given in Appendix A of the Phase 1 report. Functional allocation diagrams (FADs) and perspective diagrams, Figures 2-2 through 2-52, are included at the end of this section (page 2-27). In addition, detailed PFDs, FADs, plan views, and perspective views for the systems and subsystems are included in Appendix A of this report.

2.1 System A: Conventional Rotary Kiln

2.1.1 System A-1: Rotary Kiln, Air Combustion Gas, Dry-Wet APC (Baseline System)

System A-1 is the baseline system against which other systems are compared. The system consists of all structures, buildings, and equipment needed to accomplish the functional and operational requirements (F&ORs). The majority of the technologies in this system use proven equipment that is commercially available. The system employs a rotary kiln incinerator using air as the combustion gas. This is similar to treatment systems used by DOE at the TSCA incinerator at Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee. The APC subsystem is based on dry filtration followed by wet offgas scrubbing. The Scientific Ecology Group (SEG) incineration facility at Oak Ridge uses this general approach in its APC. Solid residues from the system are stabilized by a combination of vitrification and polymer solidification. Vitrification additives, if required, are introduced as part of the feedstock to the kiln. Contaminated soil from environmental restoration programs may be used as an additive. System A-1 has twelve subsystems, described below.

Figure 2-1. Perspective view of integrated thermal treatment system (Systems A-1 through A-6).
NOT TO SCALE

Table 2-1. Sizes and concepts of the subsystems compared to those of the baseline system (System A-1).

Subsystems	Systems								
	A-7 Slagging rotary kiln	C-2 Plasma fur- nace, CO ₂ retention	C-3 Plasma gasifi- cation	F-1 Molten salt oxi- dation	G-1 Molten metal waste destruc- tion	H-1 Steam gasifica- tion	J-1 Joule-heated vitrification	K-1 Thermal desorption and mediated electro- chemical oxidation	L-1 Thermal desorption and supercritical water oxidation
Administration	A-1 ^a	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1
Receiving and preparation	A-1	A-1	A-1	A-1 but larger	A-1 but small er	A-1 but larger	A-1	A-1	A-1
Main thermal treatment	Slagging rotary kiln	Plasma fur- nace	Plasma furnace	Molten salt oxi- dation	Molten metal waste destruc- tion	Steam gasifica- tion	Joule-heated vitrification	Thermal desorption	Thermal desorption
Main thermal treatment APC	A-1	Same as A-4	A-1	Dry/wet APC	Dry/wet APC	Dry/wet APC	A-1	Condenser and thermal oxidizer	Condenser and ther- mal oxidizer
Liquid organic waste treatment	NR ^b	NR	NR	NR	NR	NR	NR	Mediated electroche- mical oxidation	Super critical water oxidation
Salt recycling	NR	NR	NR	Evapora- tor/crys- tallizer	NR	NR	NR	NR	NR
Lead recovery	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1
Mercury amal- gamation	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1
Metal decontami- nation	A-1	A-1	A-1	A-1	NR	A-1	A-1	A-1	A-1
Metal melting	NR	NR	NR	A-1	NR	A-1	A-1	A-1	A-1
Special waste processing	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1
Aqueous waste treatment	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1
Primary stabiliza- tion	NR	NR	NR	A-1 but larger	NR	A-1 but larger	NR	Grout (Same as E-1)	Grout (Same as E-1)

Table 2-1. (continued).

Subsystems	Systems								
	A-7 Slagging rotary kiln	C-2 Plasma fur- nace, CO ₂ retention	C-3 Plasma gasifi- cation	F-1 Molten salt oxi- dation	G-1 Molten metal waste destruc- tion	H-1 Steam gasifica- tion	J-1 Joule-heated vitrification	K-1 Thermal desorption and mediated electro- chemical oxidation	L-1 Thermal desorption and supercritical water oxidation
Secondary stabi- lization	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1
Certification and shipping	A-1	A-1	A-1	A-1	A-1	A-1	A-1	A-1 but larger	A-1 but larger
a. Same as used in System A-1 b. NR - Not required.									

2.1.1.1 Receiving and Preparation Subsystem. This subsystem has cranes and forklift trucks to unload waste containers from incoming vehicles. The physical state of the waste in containers is identified by a real-time radiography (RTR) unit. The wastes are classified either assorting required (SR) waste or sorting not required (SNR) waste. A passive/active neutron (PAN) assay unit determines the level of TRU contamination of the waste. A segmented gamma scanning (SGS) unit is used to assay beta and gamma radioactivity. A bar code scanning unit records the waste for computer tracking. Containers of SNR waste are moved directly to the thermal treatment subsystem. If the SR waste container has restricted items, it is passed through a sorting train. The container is decapped by a saw mounted on a gantry robot. After decapping, the container is emptied onto a sorting table equipped with master-slave and hydraulic manipulators used for removing restricted materials, such as large pieces of metal and lead, and mercury containers. The segregated waste is sent to the appropriate treatment subsystems. For purposes of this study, approximately 50% of the waste was assumed to require sorting. Figure 2-2 shows a FAD for the receiving and preparation subsystem. Figures 2-3 and 2-4 show perspective views of the two main areas of the subsystem.

2.1.1.2 Incineration Subsystem. The incineration subsystem receives combustible and noncombustible solids, sludges, and organic liquids. Some of the sludge from the aqueous waste treatment subsystem is also fed to the unit for drying and subsequent solidification with ash. Unless special precautions are taken, sludges have a tendency during drying to form small surface-hardened balls that resist complete destruction of organic material. This tendency can be countered by introducing the sludge into the rotary kiln as small particles ($< 1/4$ -inch in diameter) or by introducing it with other wastes. The subsystem consists of a feed preparation shredder, a characterization unit, a natural gas and air fired rotary kiln, a secondary combustion chamber (SCC), an air blower, and the associated combustion and feedstock preparation equipment. The size reduction unit shreds intact drums and boxes and feeds them to a series of transport bins and hoppers. The contents of each hopper are sampled, characterized, and fed to the incinerator. Incineration takes place in a negative pressure air environment. The incinerator has a set of special graphite and steel seals designed to minimize air in-leakage.¹ A metal housing around the incinerator unit provides secondary confinement. Figure 2-5 shows the incineration subsystem FAD, and Figure 2-6 shows a perspective view.

2.1.1.3 Incineration Air Pollution Control Subsystem. The incineration APC subsystem has a dry gas filtration unit, a wet gas scrubbing unit, and a system for continuous emissions monitoring (CEM). In the dry gas filtration unit, the gas is partly quenched by water jets and filtered in either a baghouse or through high-temperature ceramic filters followed by high-efficiency particulate air (HEPA) filters. A charcoal or activated carbon filter is added in front of the HEPA filter to remove any trace quantities of mercury that might be present in the offgas. The wet offgas unit consists of a complete water quench, followed by hydrosonic and packed-bed scrubbers for removal of acid gas. A system to remove nitrogen oxides and dioxins is also included. The CEM unit monitors and records the quantities of CO, CO₂, O₂, particulates, and other compounds discharged from the stack to check compliance with air discharge permits. A continuous radiation sampling device that detects and reports radioactivity is also included at the stack discharge. Figure 2-6 shows a perspective view of the APC subsystem, and Figure 2-7 shows the FAD.

2.1.1.4 Lead Recovery Subsystem. This subsystem has a decontamination train and an electrically heated roasting oven. The decontamination train has mechanical devices, including saws,

shears, and sanders to cut and remove metal cladding from lead. Decontamination of lead takes place in scarfing and abrasive blasting booths. The oven is used to melt lead that cannot be decontaminated by mechanical means. The furnace APC subsystem has dry gas filtration similar to that of the APC subsystem provided for the rotary kiln. Figure 2-8 shows the FAD for the lead recovery subsystem, and Figure 2-9 shows a perspective view.

2.1.1.5 Mercury Amalgamation Subsystem. This subsystem uses a retort followed by a condenser to reclaim mercury from contaminated solids. After mercury removal, the solids are sent to the primary stabilization subsystem. Offgas from the mercury condenser is treated in a secondary combustion chamber and a wet-dry APC system similar to the incineration APC. Recovered elemental mercury is either recycled or amalgamated with zinc or copper in an amalgamation reactor. Figure 2-10 shows the FAD for the mercury amalgamation subsystem, and Figure 2-11 shows a perspective view.

2.1.1.6 Metal Decontamination Subsystem. This subsystem has a decontamination train with size reduction tools (plasma torch, saw, and shear) and abrasive liquid blasting booths designed to remove entrained and surface contamination. Dry ice blasting is assumed to reduce the quantity of liquid waste generated. Figure 2-12 shows the FAD for the metal decontamination subsystem, and Figure 2-13 shows a perspective view.

2.1.1.7 Metal Melting Subsystem. This subsystem includes a size reduction unit operation. Metals that cannot be decontaminated by mechanical means (surface blasting, grinding, etc.) are sent to this subsystem. In the induction melter, most radioactive material is removed in the molten slag, which is cast in a container, cooled, and sent for inspection, assay, and shipment to storage or disposal facilities. Clean molten metal is poured into an ingot, cooled, and sent for reuse or recycling. The induction melter APC subsystem has a train for dry gas filtration similar to the APC subsystem provided for the thermal treatment unit. Figure 2-14 shows the FAD for the metal melting subsystem, and Figure 2-15 shows a perspective view.

2.1.1.8 Special Waste Treatment Subsystem. It is assumed that there will be special wastes that require capabilities not included in the basic system design concept. The treatment subsystem for special waste is located in a room equipped with a crane and all utilities needed for installing treatment systems for special wastes. Special treatment systems will be identified and provided on a case-by-case basis during facility operation. A cost allowance of \$3 million for this subsystem is included in the cost estimates.

2.1.1.9 Aqueous Waste Treatment Subsystem. This subsystem collects and treats input aqueous waste, which could include wastewater having corrosive properties or contaminated with dissolved solids, suspended solids, organic compounds, or heavy metals. In addition, the subsystem treats the system's secondary aqueous wastes, such as the slurry from APC subsystem scrubber blowdown, sludge from abrasive blasting in the metal decontamination subsystem, rinse water from container washdown, and water from equipment and floor drains.

The incoming aqueous waste is segregated and stored in three batch tanks, one each for water classified as having 1) high levels of total organic carbon (TOC), 2) high levels of total dissolved solids (TDS), or 3) low levels of TDS. The primary treatment process for high-TOC waste involves removing gross organics (using flotation thickeners or coalescers), filtering out suspended solids

(using back flushable filters), removing dissolved organics (using carbon filtration or ozonators), and removing and polishing dissolved solids (using ion exchange). An alternative for treating high-TOC waste is to feed it to the thermal treatment subsystem. For liquids with high levels of TDS, the treatment involves neutralization, filtering out suspended solids, and removing dissolved solids, probably by evaporation. For liquids with low levels of TDS, the primary treatment consists of filtering out suspended solids, removing dissolved organics (using carbon filter or ozonators), and removing dissolved solids (by ion exchange).

In addition to the primary treatment trains, each waste type can be routed to or bypass a given treatment unit. The aqueous waste treatment subsystem concentrates all sludge waste produced by the various treatment processes and sends it to the stabilization subsystem. Spent ion exchange resin from treatment processes is dewatered and sent to the thermal treatment subsystem or to the stabilization subsystem.

Liquid wastes with mercury contamination are treated by precipitation and filtration using sulfur-impregnated carbon filters. Also, the ion exchange vessels will have mercury-selective resins to capture mercury. Figure 2-16 shows the FAD for the aqueous waste treatment subsystem, and Figure 2-17 shows a perspective view.

2.1.1.10 Primary Stabilization Subsystem. The primary stabilization subsystem uses vitrification to convert the incinerator ash to a waste form suitable for disposal. In vitrification, soil (including contaminated soil from a DOE installation) or chemical additives (SiO_2 , Al_2O_3 , Fe_2O_3 , etc.) that act as glass formers are metered into the rotary kiln along with the waste. The additive quantities are proportional to the weight of expected bottom ash, so characterization of the input waste must be accurate enough to predict the quantity of ash. The kiln mixes the soil with the ash and discharges the mixture into a storage hopper. The mixture is metered from the hopper into a melter furnace, which vitrifies the ash and soil mixture and discharges the molten mixture into a container. The container is cooled, capped, and sent to a swiping and decontamination station. If surface contamination is found, the container is washed by high-pressure water jets. The inspected container is sent for assay, certification, and shipping to storage or disposal facilities. The melter furnace APC unit has a dry gas filtration train similar to the dry APC subsystem provided for the rotary kiln. Figure 2-18 shows the FAD for the primary stabilization subsystem, and Figure 2-19 shows a perspective view.

Research conducted at Idaho National Engineering Laboratory (INEL) has shown that, when combined with about 40 to 50% soil, the residue after combustion will form a good glass or ceramic waste form.^{2,3,4} Although this conclusion may not hold for all wastes processed in a short campaign, it does imply a considerable latitude in the composition for making the ash residue into glass or ceramic.

Testing on bench-scale melters at INEL has shown that drying the soil before placing it in a melter results in less violent melter startup. Thus, the soil is introduced into the incinerator and dried. Additional benefits of this process are also expected. Any organic carbon will be eliminated and carbonates will be disassociated. Lastly, work sponsored by EPA at Research Triangle Park has indicated that the presence of aluminosilicates in an incinerator may reduce the volatility of some of the toxic metals. Krikorian at Lawrence Livermore National Laboratory (LLNL) has observed a reduction in actinide volatility in the presence of SiO_2 (Appendix G of Phase 1 report).

2.1.1.11 Secondary Stabilization Subsystem. The secondary stabilization subsystem receives treated residues that are not suitable for processing by the primary stabilization subsystem. Waste handled by this subsystem generally includes salts having a low melting temperature or fly ash with a salt concentration exceeding the limits specified for the primary stabilization subsystem when vitrification is used. Bulk secondary waste, such as spent filters, is compacted and macro-encapsulated by grouting techniques. Figure 2-20 shows the FAD for the secondary stabilization subsystem, and Figure 2-21 shows a perspective view.

Stabilization of salts involves polymer encapsulation using sulfur cement, polyethylene, or polymerizing agents produced by Dow Chemical Company. The subsystem has a dryer that removes water from the incoming waste. The dried powder and polymer are metered into an extruder that heats and mixes the polymer with powdered waste. The extruder feeds the mixture into a drum. When filling is complete, the drum cap is secured automatically and the drum is sent to a swiping and decontamination station. If surface contamination is detected, the container is washed by high-pressure water jets or blasts of dry ice. The inspected container is sent for assay, certification, and shipping to storage or disposal facilities.

2.1.1.12 Certify and Ship Subsystem. The certify and ship subsystem characterizes the physical and radiological properties of the packaged waste to allow certification in accordance with transportation, storage, and disposal requirements. The containers of packaged waste are weighed. An RTR unit examines the container to ensure that the matrix is homogeneous and has no free water. If TRU or alpha contaminated waste is processed, the TRU concentration is measured by a PAN assay unit. An SGS unit is used to assay the beta and gamma radioactivity. After inspection, the waste is either sent to a temporary storage area or loaded onto a truck for offsite or onsite shipment. Figure 2-22 shows the FAD for the certify and ship subsystem, and Figure 2-23 shows a perspective view.

2.1.2 System A-7: Slagging Rotary Kiln

The slagging rotary kiln system accomplishes both incineration and vitrification in a single step. Combustible and noncombustible solids along with glass-forming material or contaminated soil are added to the kiln. The kiln output is a vitrified slag that requires no further stabilization. Gas produced during the slagging process is sent to a SCC for complete oxidation. The SCC is followed by the same wet-dry APC subsystem used in the baseline case. The offgas is quenched, filtered, and scrubbed for acid gas. Abatement for nitrogen oxides is provided. Continuous emission monitoring is performed before offgas discharge. Aqueous secondary waste streams are treated in an aqueous waste treatment subsystem. The treated water is recycled into the system, as required, for process use. Costs and design data are based on information compiled from vendors (see list in Section 7).

System A-7 has eleven major subsystems, which are listed in Table 2-1. System A-7 does not have a metal melting subsystem, because metal with entrained contamination is fed to the slagging kiln and is incorporated into the discharged slag. Also, since the kiln is a one-step oxidation/stabilization unit, a separate vitrification subsystem similar to that of the baseline system is not needed.

Figures 2-24 and 2-25 show the FADs for the main thermal treatment and APC subsystems, respectively. Figure 2-26 shows a perspective view of the overall system. As indicated in Table 2-1,

most of the subsystems are the same as those of the baseline system (A-1), with the exception of the main thermal treatment subsystem. This main thermal treatment subsystem is described below. Refer to the Phase 1 report for a description of the subsystems that are similar to the baseline system.

The main thermal treatment subsystem consists of a storage and characterization area, a rotary kiln fired by natural gas and air, an SCC, an air blower, and the associated combustion and feedstock transfer equipment. The thermal treatment subsystem receives combustible and noncombustible solids, metal with entrained contamination, sludge, and organic liquid. The slagging kiln performs the organic destruction and stabilization functions in one step. The slagging kiln is able to process various types of solids, including shredded bulk waste, waste in fiber packs, and sludge.

The slagging rotary kiln is a commercial technology currently employed for hazardous waste treatment in Europe and in the United States. For more uniform and puff-free combustion, the slagging kiln selected for this study is designed to treat shredded waste. Slagging kilns can be designed to accept unshredded waste, including 55-gallon drums, but there will be a high probability of occasional thermal excursions and puffs resulting in escape of incompletely combusted material to the outside environment. This subsystem includes a shredding capability to reduce the size of input waste as needed for characterization. The size reduction unit shreds input waste and feeds it to a series of transport bins. The contents of each bin are sampled, characterized, and fed to the incinerator.

Some of the sludge from the aqueous waste treatment subsystem is also fed to the unit for drying and subsequent solidification with the slag. As the waste is fed into the kiln, necessary burner adjustments are made to maintain design levels of combustion and waste slagging. The kiln is equipped with graphite seals designed to minimize air leakage into or out of the kiln.

Incineration and slagging take place in a slightly negative-air-pressure environment (about 1 inch of water). The typical temperature range for the slagging kiln is 1500 to 2500°F. The slagging kiln can also be operated at lower temperatures in the ashing mode. The residence time of solids in the kiln is typically one hour. The destruction of solids in the slagging mode is expected to be enhanced relative to the ashing mode because of the increased heat transfer rate. The kiln has seals at the waste inlet, the slag outlet, and the entrance to the attached SCC unit. A typical design includes a combination slag pot and SCC, which is attached to the kiln. The SCC is a refractory-lined vertical cylinder, operated at a combustion temperature of 2500°F. At the bottom of the SCC, a sloped opening provides an exit for the liquid slag (or ash, if operated in the ashing mode).

Slag from the bottom of the SCC is discharged through a freeze valve into a waste container. When the container is full, the valve shuts off slag flow. The filled container is moved to a cooling and curing area. A coring device may be used to drill and extract a sample of the cured slag for analysis and characterization. The slag container is capped and sent to a decontamination station. If surface contamination is found, the container is washed by high-pressure water jets. The inspected container is sent for assay, certification, and shipping to storage or disposal facilities.

The slag discharge operation takes place in an air-sealed chamber. The chamber has an exhaust fan that collects gas and particulates from the slag pour area. The fan exhaust is sent to a baghouse filter and then discharged to the building ventilation HEPA filter units.

2.2 System C: Plasma Furnace

2.2.1 System C-2: Plasma Furnace, CO₂ Retention

The plasma furnace with oxygen combustion and CO₂ retention is an alternative to the conventional plasma furnace system (C-1) in the Phase 1 report. This system has been developed to study the effect of using oxygen for combustion and removing CO₂ from the offgas, resulting in discharge of a minimum amount of offgas to the environment. In this system, the plasma furnace performs three functions: thermal treatment, vitrification, and metal melting. The plasma furnace requires only that bulk lead and mercury be removed and treated separately, and that bulk metal and large debris be reduced in size to fit into the feed handling system and the plasma chamber. The plasma furnace can accept bulk feed, including drums. This mode of operation is used only if the waste is adequately characterized to meet the RCRA permit restrictions. Contaminated soil or other glass- or ceramic-forming additives are added to the furnace to produce a highly leach-resistant vitrified waste form. Molten solid residues from the plasma furnace, including radionuclides, are drawn off as a vitrified material. Costs and design data are based on information compiled from vendors (see list in Section 7).

The SCC is followed by a dry APC subsystem, modified to include carbon dioxide absorption of the offgas into lime, similar to System A-4 (in the Phase 1 report). This system includes removal of chlorides, CO₂, and water in the offgas in a fluidized bed. The remaining offgas, primarily oxygen, is recycled to the furnace. A small bleed-off stream from the offgas recycled to the furnace is also discharged to the atmosphere. The CO₂ is absorbed in lime to form calcium carbonate. After a given retention period, the carbonate is calcined to release the CO₂, allowing the recycle of the lime. The CO₂ released from the calcining operation is monitored and discharged to the atmosphere.

Solid residues from the plasma furnace, including radionuclides, are drawn off as a vitrified material. Aqueous secondary waste streams are treated in an aqueous waste treatment subsystem. Sludge resulting from precipitation and filtration is transferred to either the plasma furnace or, if necessary, to a secondary, polymer-based stabilization subsystem. Figures 2-27 and 2-28 show the FADs for the main thermal treatment and air pollution control subsystems, respectively. Figure 2-29 shows a perspective view of the overall system.

System C-2 has eleven major subsystems, which are listed in Table 2-1. This system does not have a metal melting subsystem because metals with entrained contamination are melted in the plasma furnace and recycled when possible. Also, since the plasma furnace is a one-step oxidation/stabilization unit, a separate vitrification subsystem similar to that of the baseline system is not needed.

As indicated in Table 2-1, most of the subsystems are the same as the baseline system (A-1), with the exception of the main thermal treatment and the APC subsystems. These two subsystems are described below. The reader is referred to the Phase 1 report for a description of the subsystems that are similar to the baseline system.

2.2.1.1 Main thermal treatment. The main components of the thermal treatment subsystem are a waste feed preparation unit, a plasma furnace, and an SCC. Waste arrives at the thermal

treatment area either in transfer bins or drums. Waste that has been characterized is fed to the plasma furnace feeder, which is an integral part of the furnace. Waste requiring size reduction and characterization is fed to a shredder. The shredder output is discharged into transport bins. Waste in each bin is sampled and characterized as required by the RCRA permit. The characterized waste is then fed to the furnace. Contaminated soil or other glass- or ceramic-forming additives are metered into the furnace.

The plasma furnace uses an electric arc. The arc produces highly energized plasma that breaks the chemical bonds of organic waste materials. Plasma gasifiers usually operate in a pyrolytic or starved-air mode in an attempt to minimize high-temperature formation of undesirable nitrogen oxides. The resulting gas from the furnace is burned in an SCC using oxygen as the combustion gas. Because of the recycling of the offgas stream back to the furnace, this system is designed to minimize air leakage into the furnace through the feed system. Monitoring of the recycled gas stream and the oxygen feed is performed to control the furnace.

Solids are periodically drawn off in a molten stream. The molten stream is collected as stabilized vitrified material in a container. During the short time required for solids removal, feed to the reactor is discontinued. The vitrified waste produced in the plasma furnace is cooled in a chamber below the furnace. The container of slag is then capped and sent to a decontamination station. If surface contamination is found, the container is washed by high-pressure water jets. The inspected container is sent for assay, certification, and shipping to storage or disposal facilities.

2.2.1.2 Main thermal treatment APC. The APC subsystem with CO₂ retention uses the same concept as System A-4 (presented in the Phase 1 report), which is based on research performed at Argonne National Laboratory. This APC subsystem treats offgas by conventional means and then removes carbon dioxide by absorption into lime in a fluidized bed reactor. Offgas treatment consists of a quench to cool the offgas and filtration by a baghouse. Further removal of particulates and metal is achieved by activated carbon and HEPA filters. Chlorides are removed and acids are neutralized in a dry scrubber, using lime as a neutralizing agent. Particulates collected from the spray dryer are sent to polymer stabilization. This removes chlorides from the recycled gas loop.

The gas stream passes through a reheater before the fluidized bed CO₂ absorber. The fluidized bed absorber, which uses lime to absorb CO₂, operates at 650°C. The treated offgas is passed through a hot cyclone, followed by a ceramic filter to remove calcium carbonate and lime particulate. This particulate stream is separated for recycling in the CO₂ recovery process.

The remaining offgas is condensed to remove water, which is transferred to the aqueous waste treatment subsystem. The treated offgas, primarily oxygen, is recycled to the furnace; the percentage of offgas recycled is based on pressure buildup in the system. A side stream is removed from the treated offgas recycle stream to prevent buildup of inert gas in the closed-loop system. The side stream gas is condensed and sent to delay tanks before discharge.

As in System A-4, the carbon dioxide held in the fluidized bed can be recovered either onsite or at a remote location by calcining the calcium carbonate. System C-2 includes onsite recovery using a rotary kiln operated at 900°C as a CO₂ desorber. Feed to the calciner includes calcium carbonate and lime particulate removed in the cyclone and filters following the fluidized bed. An indirectly heated kiln will be used as the calciner.

Calcliner offgas (primarily CO₂) is cooled and filtered through a quench and a baghouse. The calciner offgas is compressed to about 30 psi, cooled, and combined with the side stream gas in delay vessels. The combined offgas in the delay tanks is sampled before discharge. Abatement of nitrogen oxides is not included, due to the recycling of the furnace offgas and the smaller volume of nitrogen present in the system. The tested offgas is passed through final HEPA filters and released to the atmosphere.

The dry lime discharged from the kiln is stored until needed. Ninety percent of the lime is recycled to the fluidized bed. The remaining 10% is either used in the spray dryer or sent to stabilization. The lime is slaked with water before use in the spray dryer. Make-up lime is added to the fluidized bed as needed.

2.2.2 System C-3: Plasma Gasification

This system is based on a conventional plasma furnace that operates in an oxygen-starved environment. It is designed to study the effect of operating a plasma furnace in a reducing mode and producing a synthesis gas that not only reduces the volume of offgas discharged to the environment, but produces an offgas that can be used for energy recovery. In this system, air is used as the torch gas, with steam added to the furnace to provide the oxidant. Costs and design data are based on information compiled from vendors (see list in Section 7).

The plasma furnace using steam performs two functions simultaneously: thermal treatment and vitrification. The plasma furnace requires that bulk lead and mercury be removed and treated separately and that bulk metal and large debris be reduced in size to fit into the feed handling system and the plasma chamber. The plasma furnace can accept shredded feed. Contaminated soil or other glass- or ceramic-forming additives are added to the furnace to produce a leach-resistant vitrified waste form. Molten solid residues from the plasma furnace, including radionuclides, are drawn off as a vitrified material.

Since the thermal treatment process is a reduction reaction (i.e., oxygen-starved environment), the plasma furnace exhaust contains synthesis gas (referred to as syngas), which is primarily H₂, CO, and CO₂. The syngas contains impurities, such as acidic gases and particulates, that must be removed. The syngas cleaning function is accomplished in an APC subsystem consisting of quenching, dry filtration, and wet scrubbing steps. The cleaned gas is either recovered by burning in a steam boiler or sent to a thermal oxidation unit for conversion of H₂ and CO to H₂O and CO₂ and subsequent release to the atmosphere. Fly ash recovered from the APC dry filtration step is recycled to the plasma furnace. Sludges containing salts resulting from the APC wet scrubbing step are transferred to the secondary, polymer-based stabilization subsystem. The treated water is recycled into the system, as required, for process use. Figures 2-30 and 2-31 show the FADs for the main thermal treatment and air pollution control subsystems, respectively. Figure 2-32 shows the perspective view of the overall system.

System C-3 has eleven major subsystems, which are listed in Table 2-1. This system does not have a metal melting subsystem because metals with entrained contamination are melted in the plasma furnace and recycled when possible. Also, since the plasma furnace is a one-step oxidation/stabilization unit, a separate vitrification subsystem similar to that of the baseline system is not needed.

As indicated in Table 2-1, most of the subsystems are the same as those of the baseline system (A-1), with the exception of the main thermal treatment and the APC subsystems. These two subsystems are described below. The reader is referred to the Phase 1 report for a description of the subsystems that are similar to the baseline system.

2.2.2.1 Main thermal treatment. The main components of the thermal treatment subsystem are a shredder and a plasma furnace, which uses a transferred electric arc contacting the slag layer as the anode. The furnace typically operates with a 3000°F wall temperature and 1800°F gas temperature. Heat is produced in the reactor chamber by the plasma torch. Steam is added to the chamber to provide an oxidant and to encourage the formation of carbon monoxide. The furnace operates in a reducing mode. The organics react with superheated steam, forming CO, CO₂, and H₂. The offgas consists primarily of H₂, CO, and CO₂. Metal will melt and sink to the bottom of the melt. Inorganic material forms vitrified slag, which is cooled into a stable waste form. The primary stabilization subsystem collects and cools this metal-slag mixture.

The vitrified waste produced in the plasma furnace is cooled in a chamber below the plasma furnace. The melt discharge operation takes place in an air-sealed chamber that has an exhaust fan to collect gas and particulates from the melt pour area. The fan exhaust is sent to a baghouse filter and is discharged to the building ventilation HEPA filter units. The slag container is capped and sent to a decontamination station. If surface contamination is found, the container is washed by high-pressure water jets. The inspected container is sent for assay, certification, and shipping to storage or disposal facilities.

2.2.2.2 Main thermal treatment APC. The APC subsystem is based on quenching and filtration followed by wet scrubbing of the syngas. This subsystem is similar to that of the baseline system. The hot syngas exits the reactor at 1800°F and is quenched to 350°F. The quench is followed by a fabric filter baghouse to remove coarse and fine particulates. The fly ash and solids are transferred back to the plasma furnace. The syngas is passed through a charcoal or activated carbon filter for mercury removal, followed by HEPA filters. A wet scrubber is used to remove acid gases. The syngas then is sent either to a steam boiler for energy recovery or passed through a thermal oxidizer to oxidize the H₂ and CO. The oxidized syngas is monitored before discharge. The CEM unit records the quantities of CO, CO₂, O₂, particulates, and other compounds discharged from the stack to check compliance with air discharge permits. A continuous radiation sampling device that detects and reports radioactivity is also included at the stack discharge.

2.3 System F-1: Molten Salt Oxidation

The MSO subsystem is comprised of a thermal treatment subsystem, an APC, a salt recycle subsystem, and a primary stabilization subsystem with an independent APC. Combustible waste is oxidized in a molten salt bed; the molten sodium carbonate acts as a catalyst. The bed also neutralizes halogenated acids and forms halogenated salts. Noncombustibles, such as metal and salt, collect in the bed and are removed by continuously transferring some of the salt bed into a collection vessel. The melt overflow from the thermal treatment subsystem is transferred to a salt recycling subsystem, where the ash is filtered out and sent to a primary stabilization subsystem and sodium carbonate salt is recovered and recycled back to the thermal treatment subsystem. An APC subsystem, which is based on dry filtration followed by wet scrubbing, is provided for treatment of

the gas fumes from the MSO vessel. Fly ash from the APC subsystem is sent to a secondary stabilization subsystem where it is solidified with polymer. The fly ash consists mostly of salts. Since MSO can accept only combustible waste, all of the noncombustible waste is sent directly to the primary stabilization subsystem. In the primary stabilization subsystem, noncombustible solids and ash are vitrified and packaged for certification and shipping. Costs and design data are based on information compiled from vendors (see list in Section 7).

The MSO system has fourteen major subsystems, listed in Table 2-1, including a salt recycle subsystem. Most of the subsystems are the same as the baseline system (A-1) (see the Phase 1 report). Subsystems that are different from the baseline system are described below (i.e., the main thermal treatment, main thermal treatment APC, MSO salt recycle, and primary stabilization subsystems). Since the MSO thermal treatment unit processes only combustible waste, the sorting operations in the receiving and preparation subsystem are more extensive and, hence, that subsystem is larger than that included in the baseline system. Figures 2-33, 2-34 and 2-35 show the FADs for the main thermal treatment, air pollution control, and salt recycle subsystems, respectively. Figure 2-36 shows a perspective view of the overall system.

2.3.1 Main Thermal Treatment

The waste is reduced in size and separated into combustible and noncombustible categories. The combustibles are processed in the molten salt oxidation subsystem, and the noncombustibles are processed in the primary stabilization subsystem. Size reduction of the combustible waste is achieved through coarse shredding and fine shredding. The combustible waste is reduced to 1/8 of an inch or smaller for transport through the feed system to assure total combustion in the bath. The combustible waste and air/oxygen are mixed in a molten sodium carbonate (Na_2CO_3) bed in an alumina-lined reactor. The molten salt oxidation reactor serves two functions: oxidation of organic waste and neutralization of acids. The molten bed is operated at temperatures of about 1400 to 1800°F to maintain the melt viscosity. The moderate operating temperature limits the formation of nitrous oxide (NO). The offgas, principally CO_2 and H_2O , is sent to the APC subsystem. Some of the melt is continuously removed to prevent the buildup of ash and other inert materials in the reactor. Salt bath viscosity control requires that the ash fraction be kept below 20% by weight. The salt must remain fluid to facilitate transfer of the melt overflow and enhance oxidation of the organic waste. The salt overflow is sent to the salt recycling subsystem.

2.3.2 Main Thermal Treatment APC

The APC subsystem has a dry gas filtration unit, wet gas scrubbing unit, and a system for CEM. In the dry gas filtration unit, the gas is partially quenched by water jets and filtered through a baghouse to remove salt carryover. Special features have been included to clean salt cakes accumulated in the reactor exhaust pipes. A centrifugal wet scrubber collector is provided downstream of the baghouse to remove any salt fumes that might have escaped the baghouse. The scrubber is followed by a reheater and HEPA filters. The salt from the baghouse is sent to the secondary stabilization subsystem. A charcoal or activated carbon filter is added in front of the HEPA filter to remove any trace quantities of mercury that might be present in the offgas. The CEM unit records the quantities of CO , CO_2 , O_2 , particulate, and other compounds discharged from the stack to monitor compliance with air discharge permits. A continuous radiation sampling device that detects and reports radioactivity is also included at the stack discharge.

2.3.3 Salt Recycling

In the salt recycling subsystem, the ash and salt mixture is cooled, crushed, and dissolved in a water tank. The mixture is then filtered, separating the ash from the dissolved salt. The ash slurry is dried and sent to the primary stabilization subsystem. The salt solution is sent to an evaporative crystallizer. The sodium carbonate will drop out of the solution in the form of crystals, because sodium carbonate has low solubility in water at room temperature. The salt crystal solution is routed to a centrifuge where the sodium carbonate salts are separated from the solution; they are later dried and recycled back to the main thermal treatment subsystem. The supernate from the solution, which contains sodium chloride, is recycled to the dissolver tank or sent to the aqueous waste treatment subsystem for further treatment. The evaporated water collected from drying the ash sludge, sodium carbonate concentrate, and the evaporative crystallizer is condensed and sent to aqueous waste treatment or recycled to the dissolver tank.

2.4 System G-1: Molten Metal Waste Destruction

The main thermal treatment unit in System G-1 is based on a molten metal waste destruction technology. This technology is offered by several companies. DOE currently has a Program Research and Development Agreement with one vendor to study the application of molten metal technology for recycling radioactive scrap metals, including metals containing RCRA-controlled toxic organics. The molten metal waste destruction system described here uses a reactor containing a molten metal bath. The catalytic and solvation effects of the metal on the incoming feed convert them to their elemental forms. Solids and gaseous additives and catalysts (e.g., oxygen, slag formers, fluxing agents, lime, and carbon) are injected into the molten bath in order to separate radionuclides or other contaminants from the recoverable material in the feedstock. The recoverable material is sent for recycle and reuse.

A key feature of the molten metal waste destruction process is the ability to accomplish, in a single process train, three major steps: organic destruction, residue stabilization, and conversion of the recoverable material for either reuse within the plant or recycling at other facilities. While destroying the incoming waste, three phases form in the molten metal reactor: molten metal, vitreous ceramic or slag, and synthesis gas (or syngas). Although all three phases can potentially be recycled, in the ITTS study only the syngas and molten metal are assumed to be recyclable. An APC subsystem purifies the syngas by a combination of dry quenching, dry particulate removal, and wet acid gas scrubbing steps. The purified syngas is used for generating plant steam. Alternatively, syngas can be oxidized in a thermal oxidizer and discharged directly to the atmosphere. Molten metal is removed from the reactor, cast, and sent offsite for use in fabrication of waste containers and other devices that could be employed during waste management operations in the DOE complex. Molten slag containing radionuclides is removed from the reactor, poured into waste containers, and sent for storage or disposal.

System G-1 has ten subsystems, listed in Table 2-1. The ten subsystems are the same as the baseline system (A-1) with the exception of the main thermal treatment and the APC subsystems. This system does not require a metal melt or a metal decontamination subsystem. Feed is processed by the molten metal reactor and recycled. The sort unit operation in the receiving and preparation subsystem is smaller than that of the baseline system. This is due to the ability of the process to accept a wide variety of the hazardous and toxic material in the feedstock. Also, since the molten

metal reactor is a one-step organic destruction/solids stabilization unit, a separate vitrification subsystem, as provided in the baseline system, is not needed. The success of this concept is dependent on the development of a reliable shredding and feed system. Figures 2-37 and 2-38 show the FAD of the molten metal waste thermal treatment and APC subsystems, respectively. A perspective view of these subsystems is shown in Figure 2-39. The main thermal treatment and APC subsystems are described below. The reader is referred to the Phase 1 report for a description of the subsystems that are similar to those of the baseline system.

2.4.1 Main Thermal Treatment

The main component of the thermal treatment subsystem is a sealed molten metal bath reactor that operates at temperatures near 1800°C in a reducing (oxygen starved) environment. The reactor is a pressurized induction-heated melter vessel with an enlarged head space designed for control and removal of the material from gaseous or molten phases. The subsystem's waste preparation unit operation includes a coarse shredder that reduces the bulk solids to approximately 3 inches. The bulk solids discharged from the shredder are collected in air-tight transportable bins and set aside in the feed preparation area. On demand, a given waste bin is lifted and placed on top of a feed mechanism mounted above the reactor. The feeder transfers the waste to the molten metal reactor through a lock-hopper connected to a lancing pipe inside the reactor. The pipe injects the waste at the desired depth in the molten bath. In the molten bath, the waste decomposes to its elemental form. Ferrous metals are chemically reduced and held in the molten metal phase. Ceramic- and glass-forming elements float to the top in a slag phase. A selected set of glass formers, additives, and catalyzers are added to the molten bath.

The subsystem has a bulk material mixing station provided to mix the waste and solid additives, such as fluxes. Gaseous additives are fed to the reactor via tuyeres (pipes with sparge nozzles) located in the bottom of the reactor. A liquid waste feed unit operation is provided to pump the waste to the reactor via tuyeres. Fine particles ($< 100 \mu\text{m}$), such as fly ash from the APC baghouse, can also be injected into the molten bath via tuyeres.

The gaseous phase normally operates in a reducing atmosphere, with substoichiometric addition of oxygen for syngas production. The syngas on top of the molten bath is generally composed of a combination of carbon monoxide (CO), hydrogen (H_2), volatilized heavy metals, and impurities such as acidic gases and particulates. Nitrogen gas is injected into the reactor as a purge when opening the reactor for sampling or bulk addition. This prevents the intrusion of ambient air and maintains the reducing atmosphere in the reactor. The reactor exhaust is sent to the APC for treatment before either oxidizing or recycling the syngas.

The molten slag or metal is selectively discharged out of the reactor. In an air-sealed environment, the molten metal or slag is poured into a container, and then transferred to another chamber for cooling. After cooling, containers with recyclable cast metal are sent to an assay and certification station while containers with slag are sent to a capping station. After capping, slag containers are sent to a wipe test and decontamination station. If wipe tests show surface contamination on a given container, it is washed by high-pressure water jets. The recyclable cast metal and slag containers are sent for shipping to either recycle sites or storage or disposal facilities.

High-temperature instrumentation and computer models are needed to either measure or predict parameters needed to control the molten bath chemistry and metallurgy. Some of the key parameters for which instrumentation has been developed by the system vendor are carbon concentration in the metal phase, the height of the molten metal and slag in the reactor, real-time temperature of the molten slag and metal in the reactor, and concentration of syngas constituents in the reactor head space. Studies of reactor geometry to optimize input feed, reaction turbulence, refractory life, product discharge, and maintenance are also underway by the vendor.

2.4.2 Main Thermal Treatment APC

The function of the APC is to remove enough impurities so that the syngas can be safely burned. The APC subsystem accomplishes this by a combination of dry quenching, dry particulate removal, and wet gas scrubbing steps. The dry quenching step consists of passing the syngas exhaust from the reactor through a fluidized bed cooling unit that drops the temperature from 1800°C to approximately 200-150°C. Silica sand or ceramic balls cooled by water-cooled coils are used as the fluidized medium. The sand also acts as a cold trap filter and captures most of the volatilized metal escaping the reactor. Any waste residue from the fluidized bed is sent to the main thermal treatment reactor for processing.

Cooled syngas is processed through a cyclone separator to remove the majority of solid particulates and fugitive bed media from the syngas. Additional particulate removal is accomplished by filtration through baghouse and HEPA filters. A charcoal or activated carbon filter is added in front of the HEPA filter to remove any trace quantities of volatile organic compounds (VOCs) and mercury that might be present in the gas.

Particulate-free syngas is then sent to the wet gas acid removal train. This process train consists of a wet scrubber that is designed to remove dissolved acid precursors present in the syngas. An alkali scrubber is also available as backup to provide additional acid gas neutralization if necessary. Scrubber sludge is sent to the secondary stabilization subsystem where it is dried to powder and stabilized with polymer.

The clean hydrogen- and carbon-monoxide-rich syngas is sent to a steam boiler for energy recovery or burned in a thermal oxidizer. The thermal oxidation unit operates at 600°F, where hydrogen gas is burned and trace VOCs, if any, are destroyed. Oxidized syngas is directed to the stack, which is equipped with CEM equipment that records the quantities of CO₂, CO, O₂, particulate, and other compounds discharged from the stack to ensure compliance with the offgas discharge permit. A continuous radiation sampling device that detects and reports radioactivity provides real-time monitoring of radiation activities in the stack.

2.5 System H-1: Steam Gasification

The steam gasification system is designed to accommodate conventional organic waste gasification technologies that convert the organic feedstock into ash and synthesis gas. This concept not only minimizes the amount of gas discharged to the environment, but produces a gaseous product that can be used for energy recovery. Costs and design data are based on information compiled from vendors (see list in Section 7).

The main process line consists of a thermal treatment subsystem based on steam gasification, an APC subsystem, and a syngas oxidation subsystem. The main thermal treatment subsystem processes sorted combustible waste and superheated steam in an indirectly heated reactor. The heat in the reactor breaks down the organic compounds into their elemental forms. Steam reacts with the decomposed elements to form syngas and ash. An APC subsystem purifies the syngas by a combination of wet quenching, dry particulate removal, and wet acid gas scrubbing steps. The purified syngas is used for generating plant steam. Alternatively, syngas can be oxidized in a thermal oxidizer and discharged directly to the atmosphere.

The thermal treatment unit has a low tolerance for noncombustibles in the feed. Therefore, noncombustible waste, ash from the main thermal treatment subsystem, and fly ash from the APC subsystem are routed to the primary stabilization subsystem, which uses a vitrification furnace for waste stabilization. Contaminated soil or other glass- or ceramic-forming additives are added to the vitrifier to enhance the leach resistance of the final waste form. The APC scrubber liquor is sent to the aqueous waste treatment subsystem.

The steam gasification system has thirteen subsystems, which are listed in Table 2-1. The sort unit operation in the receiving and preparation subsystem is larger than that of the baseline system. This is due to the inability of the thermal treatment unit to accept noncombustible material in the feedstock. All noncombustible material must be sorted and sent to primary stabilization.

As indicated in Table 2-1, most of the subsystems are the same as those of the baseline system (A-1), with the exception of the main thermal treatment and the APC subsystems. These two subsystems are described below. The Phase 1 report describes the subsystems that are similar to those of the baseline system. Figures 2-40, 2-41 and 2-42 show the FADs for the main thermal treatment, air pollution control, and syngas oxidation subsystems, respectively. Figure 2-43 shows the perspective view of the overall system.

2.5.1 Main Thermal Treatment Subsystem

The main component of the thermal treatment subsystem is a steam reforming reactor based on fluidized bed vessel technology. The key function of the reactor is to mix the waste with steam to decompose the organic material in a high-temperature environment. The waste feed must be reduced in size for more efficient turbulence and mixing during gasification. Hence, the feed preparation unit operation is equipped with coarse and fine shredders to reduce waste particle sizes to less than the 1/4 inch. The shredded solids discharged from the shredder outlet are collected in air-tight transportable bins, which are set aside in the feed preparation area. On demand, a given waste bin is lifted and placed on top of a feed mechanism mounted adjacent to the reactor. The feeder conveys that waste to the steam reformer reactor.

Superheated steam enters the reactor through spargers at the bottom of the fluidized bed and facilitates mixing. The reactor is heated by an indirect heat source. At operating temperatures of approximately 1300 to 1400°F, and under reducing conditions, the organics react with superheated steam to form syngas composed of CO, CO₂, H₂, and H₂O. The syngas is sent to the APC subsystem for purification and energy recovery. The bottom ash, solids, and some bed material are collected, cooled, and sent to the primary stabilization subsystem for vitrification.

2.5.2 Main Thermal Treatment Air Pollution Control Subsystem

The APC subsystem is based on dry particulate filtration followed by wet acid scrubbing and final polishing of the syngas. In the dry filtration, the syngas passes through a cyclone unit, then a ceramic filter to remove coarse and fine particulates. The captured fly ash is sent to the primary stabilization subsystem. A wet scrubber is used to remove acid gases. The scrubber liquor is sent to aqueous waste treatment. The scrubbed syngas is reheated and passed through a charcoal or activated carbon filter followed by HEPA filters.

The purified syngas is either burned in a steam boiler for energy recovery or sent to a thermal oxidation unit. After oxidation in either in the steam boiler or the thermal oxidizer, the gas is sent through a CEM unit that records the quantities of CO, CO₂, O₂, particulates, and other compounds discharged from the stack to monitor compliance with air discharge permits. A continuous radiation sampling device that detects and reports radioactivity is also included at the stack discharge.

2.5.3 Primary Stabilization Subsystem

The primary stabilization subsystem receives noncombustible waste feed from the receiving and preparation subsystem and fly ash from the main thermal treatment APC. This subsystem is the same as the primary stabilization subsystem for the molten salt oxidation system (F-1).

2.6 System J-1: Joule-Heated Vitrification

The joule-heated vitrification system is designed around a conventional glass-making melter. The intent is to use a joule-heated melter in a one-step oxidation/vitrification process for treating both combustible and noncombustible waste. Several vendors have developed, or are in the process of developing, this approach. Costs and design data are based on information compiled from vendors (see list in Section 7).

In a typical process, glass- or ceramic-forming additives or contaminated soil^e are added to the vitrification unit along with the waste. Oxygen is added to the melter to oxidize the organic compounds. The upper part of the melter is provided with a plenum to house gas that forms during combustion. Ash from the combustion and the glass-forming material mix in the melter to form a homogeneous product. Offgas from the vitrification subsystem is sent to an APC subsystem. The APC subsystem uses dry filtration followed by wet offgas scrubbing. Descriptions of the main subsystems are presented below. Figures 2-44 and 2-45 show the FADs for the main thermal treatment and air pollution control subsystems, respectively. Figure 2-46 shows the perspective view of the overall system.

The joule-heated vitrification system has eleven subsystems, listed in Table 2-1. Since the main thermal treatment is a single-step oxidation and vitrification process, a separate primary stabilization

e. For this study, it is assumed that the joule-heated melter will operate at a temperature around 1500°C in order to melt the contaminated soils that are assumed in the mass balances described in Section 3. If the system cannot operate near this temperature, the soil will have to be replaced with other reagents and a lower temperature glass will be formed. This will impact calculations on mass and volume reduction as reported in Section 3.

subsystem is not needed. As indicated in Table 2-1, most of the subsystems are the same as those of the baseline system (A-1) (see the Phase 1 report), with the exception of the main thermal treatment subsystem.

2.6.1 Main Thermal Treatment

The heart of the main thermal treatment subsystem is a vitrifier, which performs organic destruction and waste stabilization in one step. Combustible and noncombustible waste are reduced in size by a coarse shredder unit, which shreds bulk material and feeds it to a series of transport bins. The contents of each bin are sampled and characterized before being fed to the vitrifier. Liquid waste will be fed in a continuous mode to reduce unexpected spikes and allow maximum throughput. A dryer has not been considered at this point in the design, but a dryer could be used to reduce moisture in slurry and soil fed to the melter. Contaminated soil or other glass- or ceramic-forming additives (SiO_2 , Al_2O_3 , Fe_2O_3 , etc.) are metered into the vitrifier. The additives are added in quantities proportional to the weight of ash expected from the feed. Consequently, characterization of the input waste must be accurate enough to predict the level of required additives. The vitrifier mixes the soil with the waste feed, melts the mixture, and discharges a molten slag product into a waste container.

2.6.2 Glass Handling

The glass handling subsystem consists of the hardware necessary to remove molten glass from the melter and cast it into a monolith. The melter is provided with a drain assembly and metering/freeze valve to accurately control glass drawoff on an intermittent basis. Cooling of the glass below the liquidus temperature is carefully controlled to avoid cooling too quickly, which results in weaknesses, or cooling too slowly, which results in crystallization.

The cooled container of slag is capped and sent to a wipe test and decontamination station. If the wipe test results indicate surface contamination, the container is washed by high-pressure water jets. The inspected container is sent for assay, certification, and shipping to storage or disposal facilities.

2.7 System K-1: Thermal Desorption and Mediated Electrochemical Oxidation

The K-1 system is designed to accommodate flameless, low-temperature (less than 600°F) technologies for processing DOE's MLLW. In this system, the design objective is to heat combustible and noncombustible solids to vaporize low-boiling-point VOCs. This study assumes that 10% of the organic waste is sent to the desorber and volatilized. The vaporized VOCs are condensed and captured in an organic liquid form. After heating and removing the VOCs, combustible and noncombustible solid residues are stabilized in a low-temperature process such as grouting. The organic liquid is destroyed in a MEO cell, which is a low-temperature oxidation process using liquid electrolytes. Costs and design data are based on information compiled from vendors (see list in Section 7).

The heating device employed in this system is an indirectly heated thermal desorber designed to receive and heat combustible and noncombustible waste to about 600°F. Vaporized compounds

exiting the desorber are filtered in a sintered metal gas/solids separator. The gas is then cooled in a heat exchanger to remove any residual mercury. The condensed mercury is collected in a liquid container and transferred to a mercury amalgamation subsystem. A secondary heat exchanger condenses the liquid water and volatilized compounds into a liquid form. The condensed liquid is sent to a liquid organic destruction subsystem based on MEO technology. Solid residue from the desorber is transferred to the primary stabilization unit where residue is grouted.

In the liquid organic waste treatment subsystem, an MEO reactor converts the incoming organics to gaseous products. The offgas from the MEO process is treated by neutralization to remove chlorine, followed by thermal oxidation. Offgas is passed through activated carbon filters and a HEPA filter before discharge. Continuous emission monitoring is performed on the offgas before discharge. Aqueous secondary waste streams generated by the recycling of spent electrolyte are processed in a fractionator unit. Solids recovered are sent to secondary stabilization, the distillate is condensed, and the sulfuric acid is separated and recycled. The treated water can be recycled into the system, as required, for process use. Figures 2-47 and 2-48 show the FADs for the main thermal treatment and APC subsystems, and for the organic liquid waste treatment subsystem, respectively. Figure 2-49 shows the perspective view of the overall system.

As indicated in Table 2-1, most of the subsystems are the same as in the baseline system (A-1) (see the Phase 1 report), with the exception of the main thermal treatment, the main thermal treatment APC, liquid organic treatment (MEO), and the primary stabilization subsystems. Also, the aqueous waste treatment subsystem no longer has the organic liquid waste treatment function. This function has been transferred to a new subsystem, the liquid organic waste treatment subsystem (the MEO process). Subsystems that are different from those of the baseline system are described below.

2.7.1 Main Thermal Treatment

The main thermal treatment subsystem consists of a feed preparation and characterization area, an indirectly heated thermal desorber, and the associated heating and feedstock transfer equipment. The thermal treatment subsystem receives combustible and noncombustible solids and sludge. The size reduction unit shreds input waste and feeds it to a series of transport bins. The contents of each bin are sampled, characterized, and fed to the desorber. Organic liquid bypasses the desorber and is transferred directly to the organic liquid waste treatment subsystem. The rotary thermal desorber volatilizes organics and water at temperatures of 500 to 600°F. The remaining solids, which includes organics that did not volatilize in the desorber, are stabilized by cement grouting in the primary stabilization subsystem. The temperature of the desorber is kept below the melting point of most plastic materials to avoid creating excessive chlorinated gas, but is high enough to volatilize most organic compounds.

2.7.2 Main Thermal Treatment APC

The APC subsystem uses dry sintered metal filtration, two stage condensation, and carbon and HEPA filtration followed by thermal oxidation of noncondensable gases. The main purpose of the APC system is to condense water and volatile organics for treatment in the organic liquid waste subsystem. Following the desorber, gas enters the metal filter for removal of particulates. The offgas is passed through a heat exchanger designed to condense mercury for transfer to the mercury amalgamation subsystem. The second stage heat exchanger condenses water and volatile organics for

treatment in the liquid organic waste treatment subsystem. The remaining offgas passes through carbon and HEPA filters. Noncondensable gas and remaining volatile organics such as methane are combusted in a thermal oxidizer, before discharge to the atmosphere. Treated offgas is directed to the stack, which has CEM equipment to record the quantities of CO, CO₂, O₂, particulates, and other compounds discharged from the stack to ensure compliance with the offgas discharge permit conditions. A continuous radiation sampling device that detects and reports radioactivity provides real-time monitoring of radiation activities in the stack.

2.7.3 Liquid Organic Waste Treatment

The liquid organic waste treatment subsystem consists of feed characterization and batching tanks, electrolyte circulation tanks, mediated electrochemical oxidation reactors, offgas treatment by neutralization and thermal oxidation, and associated pumps and instruments. The liquid organic feed from the condenser following thermal desorption is blended with other liquid organic waste streams at the characterization tank. The liquid waste is sampled and analyzed. Characterized feed is transferred to the batch tank. The contents of the batch tank are blended with the recirculating electrolyte feed, using a static mixer, at a rate determined by the system process control. Electrolyte is recycled from the electrochemical reactors to the circulation tank. Sulfuric acid/cobalt sulfate electrolyte and water are continually supplied to the circulation tank. The ratio of input waste feed to recirculating electrolyte is approximately 2% by weight.

The MEO reactors operate at 50 to 60°C and atmospheric pressure. The electrolytic cells are packaged into modular units. An electrolyte solution of cobalt sulfate and sulfuric acid is recirculated through a series of cells in the MEO unit at rates of up to 100 gpm. Electrical energy is supplied to the anode and cathode. The oxidized metal mediator acts as the primary active oxidizer to destroy organics. The cobalt is transformed from Co²⁺ to Co³⁺ + e⁻. The metal ion reacts with organic species or water to produce a reactive intermediate such as the hydroxyl radical, which also oxidizes any organic material.

Offgas is generated at the cathode (primarily H₂) and at the anode (primarily CO₂, Cl₂ from chlorocarbons, and small amounts of O₂). The anode stream is monitored to evaluate the completeness of the reaction. The anode stream is put through a caustic scrubber to convert the chlorine to hypochlorite. Both offgas streams are put through a thermal oxidizer to react the hydrogen with air to form water and to destroy any volatile organics that may vaporize from the MEO reactor. Additional air must be added to the thermal oxidizer to control the heat generated by the hydrogen oxidation reaction.

A side stream of the electrolyte solution is bled off to prevent buildup of inert materials and to recycle sulfuric acid. The electrolyte sidestream consists of water, sulfuric acid, cobalt sulfate, metal ions, unreacted waste, and miscellaneous inorganic ions such as sulfate, nitrate, and phosphate. The bleed stream is transferred to the batch process precipitation system, which precipitates metals and solids and then filters the solids. The solids, including salts, radionuclides and other metals, are transferred to secondary stabilization for microencapsulation. The remaining liquid stream is processed through a fractionator column, which produces three streams: water and high point boiling compounds, such as nitric acid; sulfuric acid; and waste residuals. The high boiling stream and the residuals are transferred to the aqueous waste treatment system. The sulfuric acid is recycled into the

electrolyte stream. The cobalt in the bleed off stream is not recovered in this process due to the small volume of cobalt removed.

2.7.4 Primary Stabilization

The primary stabilization subsystem receives desorbed solids from the main thermal treatment subsystem, and other solid waste from the receiving and preparation subsystem. The stabilization process may be classified as macroencapsulation, which meets EPA requirements for stabilizing solid wastes that fall under the debris rule. This means that a TCLP test will not be required when debris is stabilized. The mass ratio of waste feed to grout is 50% by weight. Waste not classified as debris, such as process residues, is solidified in a media that passes the EPA TCLP test.

The subsystem has preparation and mixing, and container filling, capping, swiping, and decontamination devices. A concrete core sampling unit is also provided for obtaining TCLP samples. A grout mixer blends grout with desorbed solids and other waste that has already been shredded to small particles by the thermal treatment subsystem. Grout formulation for debris solids may consist of cement, water, and sand. The blended product is poured into containers and allowed to cure. Once the stabilized waste has solidified, containers are capped, wipe tested, washed if necessary, and moved to the certification and shipping subsystem.

2.8 System L-1: Thermal Desorption and Supercritical Water Oxidation

The L-1 system is designed to apply flameless, low-temperature (less than 800°F) technologies for processing DOE's MLLW. In this system, the design objective is to heat up combustible and noncombustible solids to vaporize low-boiling-point VOCs. The vaporized VOCs are condensed and captured in an organic liquid form. After heating and removing of the VOCs, combustible and noncombustible solid residue are stabilized using a low-temperature process such as grouting. The organic liquid is destroyed in a supercritical water oxidation (SCWO) reactor, which is a low-temperature, high-pressure water oxidation process. Several vendors have developed or are in the process of developing this approach. Costs and design data are based on information compiled from vendors (see list in Section 7). Figures 2-50 and 2-51 show the FADs for the main thermal treatment, air pollution control, and grout stabilization, and for the liquid organic waste treatment subsystems. Figure 2-52 shows a perspective view of the overall system.

In the liquid organic waste treatment subsystem, a SCWO reactor using the properties of supercritical water oxidizes organic waste to gaseous products. Supercritical water is water at a temperature above 705°F (374°C) and a pressure above 220 atmospheres (22 MPa). Supercritical water has properties different from those of subcritical water. Organic compounds that are normally immiscible in water are miscible in supercritical water. Inorganic compounds, such as salts, are almost completely insoluble in supercritical water. These properties allow a quick and complete oxidation of organic waste in the reactor vessel. Hydrogen peroxide or pure oxygen is used as the oxidant in the reaction. Salts formed from the inorganic elements that are ubiquitous in most waste streams either precipitate out of the supercritical water or are removed as offgas. This gas is normally not acidic in nature and requires minimal further treatment before it can be discharged.

Continuous emission monitoring is performed before the offgas is discharged. The precipitated salts are stabilized before disposal.

As indicated in Table 2-1, most of the subsystems are the same as in the baseline system (A-1), with the exception of the main thermal treatment, the main thermal treatment APC, liquid organic waste treatment (SCWO), and the primary stabilization subsystems. Also, the aqueous waste treatment subsystem no longer treats organic liquids. This function has been transferred to a new subsystem, the liquid organic waste treatment subsystem (the SCWO process). However, the size of the aqueous waste treatment subsystem will remain the same as the baseline system because of the added duty of treating liquid waste effluent from the SCWO process. Subsystems that are different from the baseline system are described below.

2.8.1 Main Thermal Treatment Subsystem

The main thermal treatment subsystem is similar to the thermal desorption unit provided for the K-1 system (Section 2.7.1). The reader is referred to that description of this subsystem.

2.8.2 Main Thermal Treatment APC

The main thermal treatment APC is similar to that previously described for the K-1 system (Section 2.7.2).

2.8.3 Liquid Organic Waste Treatment Subsystem

The liquid organic waste treatment subsystem consists of feed characterization, feed and additive pressurization, the SCWO reactor, and two treatment trains for liquids/solid separation and offgas air pollution control. Input waste to this system consists of organic liquids and organic sludge. Organic sludge is filtered to an acceptable size for the SCWO process. Optimal performance is achieved when the maximum particle size in the waste stream is about 100 μm . For this reason the incoming waste is batched, filtered, and tested. Material exceeding the 100 μm limit is sent to primary stabilization. The waste is tested for heat content to assist in feed preparation.

The SCWO reaction process consists of three subprocesses: feed preparation, reaction, and air pollution control. In the feed preparation step, the reactants are pressurized above 220 atm (22 MPa) and heated above 705°F (374°C). The reaction takes place in a pressure vessel. The optimum design for this vessel is still being developed, but current prototype systems use metal alloys and may use ceramics. Products from the oxidation reaction include H_2O , CO_2 , and inorganic salt precipitates. Salts are separated from the aqueous phase in an agitated thin-film filter and evaporator. The inorganic salts are sent to the secondary stabilization subsystem while the offgas is further treated by activated carbon adsorption and HEPA filtration. Liquid from the thin-film filter is polished using activated carbon and ion-exchange resins, and is then tested. Next, it is either recycled or sent for further treatment to the aqueous waste treatment subsystem.

2.8.4 Primary Stabilization Subsystem

The primary stabilization subsystem is similar to that previously described for the K-1 system (Section 2.7.4).

FIGURE B1-14. ROTARY KILN: FAD FOR RECEIVING AND PREPARATION (SYSTEM A-1)

Figure 2-2. FAD for receiving and preparation subsystem for rotary kiln using air (System A-1).

FIGURE B1-30. ROTARY KILN: PERSPECTIVE VIEW OF RECEIVING AND UNLOADING AREA OF THE RECEIVING AND PREPARATION SUBSYSTEM (SYSTEM A-1)
NOT TO SCALE

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Figure 2-3. Perspective view of receiving and unloading area of the receiving and preparation subsystem for rotary kiln using air (System A-1).

Figure 2-4. Perspective view of the decap, sort, and dump cell of the receiving and preparation subsystem for rotary kiln using air (System A-1).

Figure 2-5. FAD for the main thermal treatment subsystem for rotary kiln using air (System A-1) and rotary kiln using oxygen (System A-2).

Figure 2-6. Perspective view of the main thermal treatment and air pollution control subsystems for rotary kiln using air (System A-1).

Figure 2-7. FAD for air pollution control subsystem for rotary kiln using air (System A-1).

①	CHERRY PICKER CRANE (SI)	②	TRANSFER CART (CA)	③	ASSAY AND INSPECT (SI)	④	SIZE REDUCTION TOOL (ND)	⑤	DECONTAMINATION BOOTH (CA)	⑥	SPRAY/SLOPE PUMP (CA)	⑦	FILTER (CA)	⑧	CRIT STORAGE TANK (CA)	⑨	EXHAUST FAN (CA)	⑩	HEPA FILTER (SI)	⑪	WELTER (SI)	⑫	CANISTER (CA)
⑬	IMBED HOOK (SI)	⑭	SECONDARY COMBUSTION CHAMBER (CA)	⑮	COOLING UNIT (CA)	⑯	STORAGE BIN WASHING STATION (CA)	⑰	OVERSEER (CA)	⑱	DRY FILTER (CA)	⑲	ACTIVATED CARBON FILTER (CA)	⑳	HEPA FILTER (CA)	㉑	CONTRAST AIR MONITOR (ND)	㉒	BLOWER (CA)	㉓	HEPA FILTER (SI)	㉔	WELTER (SI)

CA = COMMERCIALLY AVAILABLE
 ND = NEEDS DEVELOPMENT
 SI = SYSTEM INTEGRATION NEEDED

Figure 2-8. FAD for lead recovery subsystem for rotary kiln using air (System A-1).

Figure 2-9. Perspective view of lead recovery subsystem for rotary kiln using air (System A-1).

Figure 2-10. FAD for mercury amalgamation subsystem for rotary kiln using air (System A-1).

Figure 2-11. Perspective view of mercury amalgamation subsystem for rotary kiln using air (System A-1).

①	CANTRY ROBOT CRANE (SI)	②	TRANSFER CHUTE (CA)	③	SIZE REDUCTION TOOL (SI)	④	DECONTAMINATION BOOTH (CA)	⑤	SPRAY/SLUDGE PUMP (CA)	⑥	FILTER (CA)	⑦	GRT OR CO2 STORAGE TANK (CA)	⑧	EXHAUST FAN (CA)	⑨	HEPA FILTER (CA)
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CA - COMMERCIALY AVAILABLE
 NO - NEEDS DEVELOPMENT
 SI - SYSTEM INTEGRATION NEEDED

Figure 2-12. FAD for metal decontamination subsystem for rotary kiln using air (System A-1).

- ① SIZE REDUCTION TABLE
- ② DECONTAMINATION BOOTH
- ③ INSPECT AND PACKAGE TABLE
- ④ GANTRY ROBOT
- ⑤ REMOTE CONTROL VEHICLE

NOTE: WALLS NOT SHOWN FOR CLARITY

NOT TO SCALE

FILENAME: MSD20.DCM PLOT DATE 04/10/94

Figure 2-13. Perspective view of metal decontamination subsystem for rotary kiln using air (System A-1).

Figure 2-14. FAD for metal melting subsystem for rotary kiln using air (System A-1).

FILENAME: JME20.DWG PLOT DATE 04/10/94

Figure 2-15. Perspective view of metal melting subsystem for rotary kiln using air (System A-1).

Figure 2-16. FAD for aqueous waste treatment subsystem for rotary kiln using air (System A-1).

NOT TO SCALE

EQUIPMENT LIST

- ① BATCH TANKS WITH AGITATOR (TYP 4)
- ② OIL AND WATER SEPARATOR
- ③ SOLIDS FILTER
- ④ NEUTRALIZER TANK WITH AGITATOR
- ⑤ REACTOR TANK WITH AGITATOR
- ⑥ SETTLING TANK
- ⑦ EVAPORATOR UNIT
- ⑧ CONDENSER
- ⑨ CONDENSED WATER TANK
- ⑩ VAPOR PHASE CARBON FILTER
- ⑪ VACUUM PUMP
- ⑫ BATCH STILL
- ⑬ STILL CONDENSER
- ⑭ VAPOR PHASE CARBON FILTER
- ⑮ ION EXCHANGE UNIT
- ⑯ UV AND PEROXIDE UNIT
- ⑰ CARBON FILTER DRUMS

NOTE: WALLS NOT SHOWN FOR CLARITY

Figure 2-17. Perspective view of aqueous waste treatment subsystem for rotary kiln using air (System A-1).

Figure 2-18. FAD for primary stabilization subsystem for rotary kiln using air (System A-1).

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

Figure 2-19. Perspective view of primary stabilization subsystem for rotary kiln using air (System A-1).

Figure 2-20. FAD for secondary stabilization subsystem for rotary kiln using air (System A-1).

Figure 2-21. Perspective view of secondary stabilization subsystem for rotary kiln using air (System A-1).

Figure 2-22. FAD for certify and ship subsystem for rotary kiln using air (System A-1).

Figure 2-23 Perspective view of certify and ship subsystem for rotary kiln using air (System A-1).

Figure 2-24. FAD for main thermal treatment subsystem for slagging rotary kiln (System A-7).

Figure 2-25. FAD for air pollution control subsystem for slagging rotary kiln (System A-7).

NOTE: WALLS NOT SHOWN FOR CLARITY

FILENAME: ATOWG2D.NEW PLOT DATE: 01/11/95

Figure 2-26. Perspective view of main thermal treatment and air pollution control subsystems for slagging rotary kiln (System A-7).

Figure 2-27. FAD for main thermal treatment subsystem for plasma furnace, CO₂ retention (System C-2).

Figure 2-28. FAD for air pollution control subsystem for plasma furnace, CO₂ retention (System C-2).

FILENAME: C20WC2D.NEW PLOT DATE: 01/11/95

Figure 2-29. Perspective view of main thermal treatment and air pollution control subsystems for plasma furnace, CO₂ retention (System C-2).

Figure 2-30. FAD for main thermal treatment subsystem for plasma gasification (System C-3).

Figure 2-31. FAD for air pollution control subsystem for plasma gasification (System C-3).

NOTE: WALLS NOT SHOWN FOR CLARITY

EQUIPMENT LIST

- ① SHREDDER
- ② PORTABLE WASTE HOPPER
- ③ WASTE FEED HOPPERS
- ④ PLASMA STEAM REACTOR
- ⑤ PLASMA TORCH
- ⑥ SLAG COLLECTION CHAMBER
- ⑦ SLAG COOLING CHAMBER
- ⑧ QUENCH COLUMN
- ⑨ DRY FILTER BAGHOUSE
- ⑩ CARBON FILTER
- ⑪ HEPA FILTER
- ⑫ HYDROSONIC SCRUBBER
- ⑬ PACKED TOWER SCRUBBER
- ⑭ THERMAL OXIDIZER
- ⑮ STACK
- ⑯ INSPECTION UNIT
- ⑰ CAPPING AND DECON UNIT
- ⑱ LIQUID WASTE TANK & PUMP
- ⑲ SOIL CONVEYOR
- ⑳ WASTE SAMPLE COLLECTOR
- ㉑ DUST COLLECTOR
- ㉒ SOIL FEED HOPPER
- ㉓ OVERHEAD CRANE
- ㉔ WASTE CONTAINER HOIST

NOT TO SCALE

FILENAME: C30WG20.DGN PLOT DATE: 01/11/95

Figure 2-32. Perspective view of main thermal treatment and air pollution control subsystems for plasma gasification (System C-3).

Figure 2-33. FAD for main thermal treatment subsystem for molten salt oxidation (System F-1).

Figure 2-34. FAD for air pollution control subsystem for molten salt oxidation (System F-1).

FILENAME: F10YG20.NEW PLOT DATE: 01/12/95

Figure 2-36. Perspective view of main thermal treatment and air pollution control subsystems for molten salt oxidation (System F-1).

Figure 2-37. FAD for main thermal treatment subsystem for molten metal waste destruction (System G-1).

Figure 2-38. FAD for air pollution control subsystem for molten metal waste destruction (System G-1).

FILENAME: G10W20-NEW PLOT DATE: 01/12/95

Figure 2-39. Perspective view of main thermal treatment and air pollution control subsystems for molten metal waste destruction (System G-1).

Figure 2-40. FAD for main thermal treatment subsystem for steam gasification (System H-1).

Figure 2-41. FAD for air pollution control subsystem for steam gasification (System H-1).

Figure 2-42. FAD for syngas oxidation subsystem for steam gasification (System H-1).

Figure 2-43. Perspective view of main thermal treatment and air pollution control subsystems for steam gasification (System H-1).

1	LIFT HOIST (CA)	2	SHREDDER INLET AIRLOCK (SI)	3	SHREDDER (CA)	4	UNLOADING AIRLOCK FLANGE (IND)	5	WASTE FEEDER (SI)	6	JOLE-HEATED VITRIFIER (SI)	7	SECONDARY COMBUSTION CHAMBER (CA)	8	BAGHOUSE (SI)	9	CANISTER (SI)	10	MELTER DISCHARGE VALVE (SI)
11	ASH OR SOIL PORTABLE HOPPER (SI)	12	SHREDDER OUTLET AIRLOCK AND LOADING FLANGE (SI)	13	PORTABLE WASTE HOPPER (SI)	14	TRANSFER DOLLY (CA)	15	WASTE SAMPLER DEVICE (SI)	16	CANISTER CHIPPING AND DECON (SI)	17	ENTRY ROBOT (RO)	18	PNEUMATIC TUBE CONVEYOR (SI)	19	SLAG COOLING CHAMBER (CA)		

PRIMARY MATERIAL FLOW
 SECONDARY MATERIAL FLOW
 CA - COMMERCIALLY AVAILABLE
 SI - SYSTEM INTEGRATION NEEDED
 RO - NEEDS DEVELOPMENT

Figure 2-44. FAD for main thermal treatment and primary stabilization subsystems for joule-heated vitrification (System J-1).

Figure 2-45. FAD for air pollution control subsystem for joule-heated vitrification (System J-1).

Figure 2-46. Perspective view of main thermal treatment and air pollution control subsystems for joule-heated vitrification (System J-1).

Figure 2-48. FAD for organic liquid waste treatment subsystem for thermal desorption and mediated electrochemical oxidation (System K-1).

Figure 2-49. Perspective view of main thermal treatment and air pollution control subsystems for thermal desorption and mediated electrochemical oxidation (System K-1).

Figure 2-50. FAD for main thermal treatment, air pollution control, and grout stabilization subsystems for thermal desorption and supercritical water oxidation (System L-1).

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Figure 2-51. FAD for organic liquid waste treatment subsystem for thermal desorption and supercritical water oxidation (System L-1).

NOTE: WALLS NOT SHOWN FOR CLARITY

EQUIPMENT LIST

- ① SHREDDER
- ② STACK
- ③ WASTE FEED HOPPER
- ④ THERMAL DESORBER
- ⑤ DISCHARGE HOPPER
- ⑥ WASTE HOPPER
- ⑦ DRY METAL FILTER
- ⑧ BATCH TANK
- ⑨ PRIMARY CONDENSER
- ⑩ SECONDARY CONDENSER
- ⑪ CARBON FILTER
- ⑫ HEPA FILTER
- ⑬ ORGANIC LIQUID TANK
- ⑭ MERCURY COLLECTION VESSEL
- ⑮ HEAT EXCHANGER
- ⑯ SUPERCRITICAL WATER REACTOR
- ⑰ OVERHEAD CRANE
- ⑱ VAPOR-LIQUID PHASE SEPARATOR
- ⑲ EVAPORATIVE WIPE FILTER
- ⑳ COOLING HEAT EXCHANGER
- ㉑ EQUALIZING VESSEL
- ㉒ FAN
- ㉓ THERMAL OXIDIZER
- ㉔ PORTABLE WASTE HOPPER
- ㉕ DUST COLLECTOR
- ㉖ WASTE CONTAINER HOIST
- ㉗ PUG MILL
- ㉘ INSPECTION STATION
- ㉙ DECONTAMINATION STATION
- ㉚ SAMPLE COLLECTOR
- ㉛ ION EXCHANGE UNIT
- ㉜ LIQUID PHASE CARBON
- ㉝ ADDITIVE FEED PUMPS

NOT TO SCALE

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Figure 2-52. Perspective view of main thermal treatment and air pollution control subsystems for thermal desorption and supercritical water oxidation (System L-1).

3. SYSTEM FLOW RATES

This section summarizes the mass flow rates of the major inputs and outputs of the systems and the methods used to make these calculations. This information is presented in several figures in this section. Detailed information on mass flow rates is presented in the process flow diagrams (see Appendix A).

The mass flow rate data used in this preconceptual design study are based on many assumptions. These assumptions, discussed below, must be validated or revised before commencing more detailed design activities.

Mass flow rates for key subsystems of the nineteen ITTS flow sheets were calculated with ASPEN PLUS (ASPEN).¹ ASPEN was used to model the main thermal treatment, main APC, primary stabilization, and metal melter subsystems. ASPEN is a simulation program that models the steady-state performance of a chemical process. The process can be as simple as a single unit operation or it can include an entire industrial plant. ASPEN is used extensively in the chemical process industry and its utility is widely recognized. The capabilities of ASPEN include chemical thermodynamics and mass and energy balances for individual unit operations as well as for the entire flow sheet. ASPEN calculates the composition of individual flow streams and it can also accept design specifications for individual unit operations. The modeling capabilities of ASPEN made it ideally suited for use in calculating the mass and energy balances for the ITTS flow sheets.

3.1 System Input Feed Rates

Tables 3-1 through 3-8 list the chemical compositions of the input waste to each of the subsystems (the tables for this section are found beginning on page 3-8). As in Phase 1, the feed rates for these systems are uniformly calculated based on 4,032 hours of operation per year for 20 years. The capacities of the modules are slightly greater than required by the waste inventory.

For the purpose of this conceptual study, the feed rate calculations are based on a total of 2,927 lb/hr to the system. The input to the various subsystems may vary, but the total feed rate to the Phase 1 and Phase 2 systems is always calculated at 2,927 lb/hr.

The main thermal treatment subsystem capacity is 2000 lb/hr when both combustible and noncombustible solids are processed by this subsystem. This is the capacity for rotary kiln systems A-1 through A-6. However, the main thermal treatment subsystem feed rate is more than 2000 lb/hr when metal is added to the combustible and noncombustible waste input. For example, the thermal treatment subsystem in two of the one-step processing systems (slagging rotary kiln and plasma furnace) can accept metal with entrained contamination in addition to the combustible and noncombustible solid waste streams.

Some of the systems have primary treatment subsystems that cannot accommodate all of the waste. For example, some of the thermal treatment subsystems (e.g., MSO and steam gasification) accept only combustible waste. The MEO and SCWO systems accept only the liquid organic fraction of the combustible waste (7.7%), the aqueous organic fraction of the aqueous waste (20.0%), and the condensed volatile organics from the desorber (18.4% of the noncombustible and remaining

combustible waste). For System E-1 (rotary kiln and thermal desorber), the rotary kiln receives all of the combustible portion of the waste and the condensed volatile organics from the desorber (21.6% of the noncombustible waste).

The molten metal waste destruction system accepts additional waste streams, such as metal with surface and entrained contamination. Hence, the input waste to the main thermal treatment subsystem of the molten metal system consists of combustible solids, noncombustible solids, metal with entrained contamination, and metal with surface contamination.

Figure 3-1 shows the volume of input waste processed by the primary thermal treatment subsystem and the liquid organic waste treatment subsystem for the nineteen systems (the figures for this section are found beginning on page 3-25). Only Systems K-1 (thermal desorption and mediated electrochemical oxidation) and L-1 (thermal and supercritical water oxidation) have a liquid organic waste treatment subsystem.

See Table 1-5 for overall subsystem inputs. Detailed information on flow rates to the subsystems is found in Appendix B.

3.2 System Secondary Waste

Waste input data in Table 3-9 show the major secondary waste streams that have been calculated in the mass balance studies. Secondary waste is produced within the facility, e.g., APC scrubber salts, decontamination subsystem sludge, spent salt from the MSO process, and spent lime from CO₂ retention systems. Secondary waste streams such as housekeeping trash, spent refractory material, or contaminated failed equipment and parts generated during maintenance are estimated to be small and the same for all systems. Hence, they are not expected to affect the outcome of the systems comparison. For cost estimating purposes, the final waste output from the latter secondary waste is assumed to be 1 cubic foot per hour. This volume is expected from waste processed from the following sources within the facility:

- Housekeeping trash, disposable garments, and equipment maintenance waste.
- Spent baghouse, ventilation, and HEPA filter elements.
- Accumulations in equipment drains and floor drains, and other liquids generated during routine flushing and cleanup of the systems, including floor wash-downs.
- Machinery oil and decontamination solutions generated during equipment replacement and maintenance.
- Spent refractory lining from thermal treatment units.
- Spent activated carbon beds, ion-exchange resins, and other filter media used in the facility.

In addition to the overall mass balance performed on the input and output streams, a balance was also performed on the amount of water required by each of the systems and the amount of water

available for recycle within each system. Some systems generated slightly more water than could be recycled; however, preliminary results indicated that the discharge of liquid effluent could be avoided by employing effective processing approaches. A discussion of the water balance results is provided in Appendix B.

3.3 Key Assumptions for Mass Flow Calculations

The key assumptions for mass flow calculations are as follows.

- Density (lb/ft³):^f
 - Vitrified waste = 187 lb/ft³
 - Polymer stabilized ash = 94 lb/ft³
 - Polymer stabilized salts = 80 lb/ft³
 - Polymer stabilized lime = 96.5 lb/ft³
 - Grout stabilized debris = 126.6 lb/ft³
 - Metal = 480 lb/ft³
 - Aqueous liquid = 62 lb/ft³
 - Soil = 67 lb/ft³
 - Input waste^{2,g} = 64 lb/ft³
- Mercury content:
 - Elemental mercury (100% Hg) comprises 5% of the waste designated as mercury-contaminated.
 - Mercury concentration in the remaining 95% of the mercury-contaminated stream is 5%.
- Stabilization formulas (all on a mass basis):
 - Vitrification = One part soil to two parts waste residue (ash or untreated inorganic waste).
 - Polymer = One part polymer to one part waste.
 - Grout = Two parts grout to one part waste.

f. Values for waste density were taken from the Phase 1 report.⁷ Other values for waste density at the INEL, in unpublished work by W. S. Roesener et al., are approximately one-half of those used in the ITTS study. It is recognized that waste density can be highly variable; however, density values affect only the calculations for volume reduction and not the overall mass balance.

g. Average density of the waste input was obtained by mass averaging the data for individual waste categories found in Table 3.3 of Reference 2.

- Feed rates
 - Systems A-1 through A-6 (rotary kiln systems) and System J-1 (joule-heated vitrification): 2,000 lb/hr, consisting of 1,340 lb/hr of noncombustible waste and 660 lb/hr combustible waste.
 - One-step thermal treatment processes, i.e., Systems A-7 (slagging rotary kiln), C-1 (plasma furnace), C-2 (plasma furnace, CO₂ retention), and C-3 (plasma gasification): 2,149 lb/hr, consisting of 1,340 lb/hr of noncombustible waste, 660 lb/hr of combustible waste, and 149 lb/hr of metal.
 - Main thermal treatment for Systems B-1 (pyrolysis), D-1 (fixed hearth pyrolyzer), F-1 (molten salt oxidation) and H-1 (steam gasification): 660 lb/hr of combustible waste.
 - Thermal desorption process for Phase 1 System E-1 (rotary kiln and thermal desorption): 1340 lb/hr of noncombustible waste fed to the desorber, 289 lb/h organics recovered during desorption sent to the rotary kiln, 660 lb/hr combustible waste fed to the kiln.
 - System G-1 (molten metal waste destruction): 2,617 lb/hr, consisting of 1,340 lb/hr noncombustible waste, 660 lb/hr combustible waste, and 617 lb/hr of metal.^h
 - Thermal desorption for Phase 2 systems: 1,950 lb/hr of combustible and noncombustible waste, excluding any organic liquid waste streams.
 - Organic liquid waste subsystems: 51 lb/hr of organic liquid as a portion of the combustible waste stream; 16 lb/hr of aqueous organic liquid as a portion of the aqueous waste stream; 358 lb/hr of organics recovered during desorption.
- Salt recovery process:
 - Salt recycle efficiency = 90% (10% rejected).
- Carbon dioxide retention process (Systems C-2, D-1)
 - Lime discarded as waste after calcining comprises 10% of the feed to the calciner.
 - Lime recycled back into system comprises 90% of the feed to the calciner.
- Metal recovery process (System A-6):

h. System G-1 can process surface contaminated metallic waste in the molten metal bed through the addition of fluxing agents to remove the radioactivity. The molten metal process can, therefore, accept the surface-contaminated metallic waste (468 lb/hr) in addition to the entrained contaminated metallic waste (149 lb/hr) for a total of 617 lb/hr of metallic waste.

- Metal separated from the incinerator feed comprises 1% of the input waste.
- Ash content:
 - Ash from combined combustible and noncombustible waste (feedstock to rotary kiln incinerator in Systems A-1 to A-5) comprises 54.0% of the feed.
 - Ash from combustible waste (feedstock to pyrolyzer in System B-1, fixed-hearth in System D-1, and rotary kiln incinerator in System E-1) comprises 7% of the feed.

Except for System J-1 (joule-heated vitrification), solids to be vitrified are dried prior to vitrification. For rotary kiln Systems A-1 through A-6, this is accomplished by feeding noncombustibles to the incinerator. In the case of System E-1 (rotary kiln and thermal desorption), only ash is fed to the vitrifier, noncombustibles are processed by thermal desorption. Systems that send unprocessed noncombustibles to the vitrifier employ a dryer prior to the vitrifier (Systems B-1, indirectly heated pyrolyzer; D-1, fixed hearth, O₂, CO₂ retention; F-1, molten salt oxidation; and H-1, steam gasification).

Soil or other glass formers are added to increase the leach resistance of the vitrified waste form. The soil additive used here is assumed to have 10% moisture by weight. As a consistent design criteria in this study, a mass ratio of 0.5:1 (soil additive: inert input) has been considered for input to the primary stabilization (vitrification) subsystem.³ Depending on the specific system, the inert input to the primary stabilization subsystem would consist of bottom ash from the main thermal treatment subsystem, fly ash from the air pollution control subsystem, and any other noncombustible feedstock to the vitrification unit.

The rationale for the above formula for vitrification stems from laboratory work performed at the INEL on vitrification of simulated stored waste residue streams. It has been determined that some wastes have a post-combustion formulation that is completely suitable for making an iron-enriched basalt glass-ceramic without the addition of other materials. It was also found that if the characterization of the incoming waste is poor, a good glass-ceramic formulation can still be achieved for essentially any waste feed composition with the addition of 40%–60% soil to the waste residue. Consequently, for this study it has been assumed that one-half pound of soil will be added to each pound of residue going to the vitrification unit operations. It is realized that by carefully selecting the waste streams, some materials will require no additives. However, it is impractical to take credit for such selection in this study, since the necessary detailed knowledge of the waste stream composition is lacking. Furthermore, the approach taken is conservative, with respect to total volume for final disposal, and thus cost estimates are conservative.

One other assumption made in this study is that for the joule-heated melter system, the relationship between waste mass and additive mass of glass-forming materials is the same as for other vitrifiers. Since the acceptable range of composition for borosilicate glass usually formed in a joule-heated melter at an operating temperature of 1,050°C is narrower than for alumino-silicates, such as iron-enriched basalt, this assumption is questionable for that system. It is likely that either better control over the incoming waste is required or that a fixed waste-to-glass former mass ratio is required. Such subtleties are currently the subject of much research and debate within DOE research programs. Consequently, for this study, all melters are treated equally.

3.4 Energy Balance Calculation Results

Energy requirements for the Phase 1 and 2 systems were calculated using ASPEN to see how energy requirements differ among the systems. The calculations included the energy required for the main thermal treatment, vitrification, and organic liquid waste treatment. While heat rejection (cooling water requirements) was calculated using ASPEN, it is not discussed here because the systems are distinguished more by the prime energy requirements than by cooling water requirements.

Results of the energy balance calculations are shown in Table 3-10. System A-6 (rotary kiln with maximum recycling) has the highest energy demand (35.7 MMBtu/hr) and System B-1 (pyrolyzer) the lowest (3.35 MMBtu/hr). Table 3-10 also contains cost estimates for the energy consumption for each of the systems. The system with the highest energy cost over 20 years, in 1994 dollars, is System A-6 (\$33.0 million). The system with the lowest energy cost is System A-5 (\$1.6 million). Although energy costs vary by over an order-of-magnitude, they have little bearing on the total life cycle costs of the systems. System economics are discussed in more detail in Section 4.

3.5 System Output

Output calculations are presented for the nineteen systems, allowing comparison of the offgas volumes and waste volume reduction for the different systems. Gaseous and solid effluents for the systems are shown in Tables 3-11 and 3-12, respectively.

The solid waste volume output from each system is presented as the sum of the outputs from subsystems sending waste to the certification and shipping subsystem. Wastes from subsystems that produce stabilized waste are included in this calculation (polymer stabilization, vitrification, grout stabilization, and special waste treatment). For one-step thermal treatment processes, the main thermal treatment also produces waste in its final form. Decontaminated metal solids, cast metal, and decontaminated lead that are recyclable are not included in the volume of waste output to disposal. Table 3-12 also shows the subsystem that generates the volume to be stabilized, e.g., the main thermal treatment produces an ash stabilized by vitrification, the primary stabilization approach. The table provides a summary of the output from the main thermal treatment and APC systems alone, as well as the total system output. The volume reduction factor or input/output ratio is also presented. System A-6, rotary kiln with maximum recycling, has the highest volume reduction factor. Systems that employ thermal desorption and grout stabilization have the lowest factors.

3.6 Mass Balance Calculation Results

Simplified block diagrams showing the key system inputs and outputs from the main thermal treatment and APC subsystems are shown in Figures 3-2 through 3-25 for the nineteen systems. Figures for the Phase 1 systems have been updated with results from ASPEN calculations. Previously reported results for the Phase 1 systems were based on less sophisticated methods, so new calculations were performed using ASPEN for consistency with the Phase 2 calculations. The mass balance tables include all of the subsystems of the respective ITTS flow sheets. Mass flow rates for the subsystems were obtained from the ITTS Phase 1 report. When all of the subsystem inputs are combined with

the primary treatment system, each of the complete ITTS flow sheets has the same waste input (2,927 lb/hr). Mass closure is very good in the summary tables; small differences (1-5 lb/hr) are attributed to numerical round off.

The inputs and outputs of the subsystems, other than the main thermal treatment and APC, are not shown on the figures. Waste input to other subsystems is shown on Table 3-9 and waste output in Table 3-12.

The results of the mass balance calculations demonstrate some significant trends with regard to minimizing offgas. Oxygen combustion provides most of the offgas reduction. Retention of CO₂ provides additional assurance that harmful pollutants are not released into the atmosphere. (The cost associated with either feature adds less than 10% to life-cycle cost.) Minimizing the volume of offgas can provide important benefits: reduced particulate carryover, reduced size and cost of APC equipment, and possible reduction of public concerns over the thermal treatment process.

Table 3-1. Elemental composition of DOE contact-handled combustible MLLW assigned to main thermal treatment in Phase 2 of the ITTS study.

Waste component	Mass %	Mass (kg)
Organics		
Carbon	49.40	18,402,950
Hydrogen	7.72	2,873,997
Oxygen	14.05	5,231,964
Nitrogen	0.03	12,772
Sulfur	0.07	27,389
Chlorine	8.03	2,990,444
Fluorine	0.02	6,296
NO	0.00	0
SO ₂	0.00	0
All organics	79.32	29,545,813
Inorganics		
Water	3.00	1,118,349
Glass-forming inerts	16.05	5,979,707
Bulk nontoxic metal	1.16	432,787
Arsenic (As)	0.00	0
Barium (Ba)	0.12	43,279
Beryllium (Be)	0.00	0
Cadmium (Cd)	0.12	43,279
Chromium (Cr)	0.23	86,557
Lead (Pb)	0.00	0
Mercury (Hg)	0.00	0
Selenium (Se)	0.00	0
Silver (Ag)	0.00	0
Tantalum (Ta)	0.00	0
Uranium (U)	0.00	0
All inorganics	20.68	7,703,957
<u>All organics and inorganics</u>	<u>100.00</u>	<u>37,249,771</u>

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993, in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Fiber-reinforced-plastic boxes are included in the above breakdown.

Table 3-2. Elemental composition of DOE contact-handled noncombustible MLLW assigned to main thermal treatment in Phase 2 of the ITTS study.

Waste component	Mass %	Mass (kg)
Organics		
Carbon	0.36	268,838
Hydrogen	0.04	30,307
Oxygen	0.11	81,363
Nitrogen	0.00	635
Sulfur	0.05	34,736
Chlorine	1.11	839,433
Fluorine	0.00	0
NO	0.05	37,279
SO ₂	0.06	46,970
All organics	1.77	1,339,562
Inorganics		
Water	26.44	19,979,396
Glass-forming inerts	71.18	53,782,441
Bulk nontoxic metal	0.00	0
Arsenic (As)	0.00	3,447
Barium (Ba)	0.00	2,023
Beryllium (Be)	0.00	0
Cadmium (Cd)	0.20	148,257
Chromium (Cr)	0.37	279,072
Lead (Pb)	0.01	9,800
Mercury (Hg)	0.01	8,605
Selenium (Se)	0.00	1,721
Silver (Ag)	0.00	1,725
Tantalum (Ta)	0.00	0
Uranium (U)	0.00	0
All inorganics	98.23	74,216,486
<u>All organics and inorganics</u>	<u>100.00</u>	<u>75,556,048</u>

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993, in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Fiber-reinforced-plastic boxes are included in the above breakdown.

Table 3-3. Elemental composition of DOE contact-handled MLLW assigned to lead recovery in the ITTS study.

Waste component	Mass %
Organics	
Carbon	0.02
Hydrogen	0.00
Oxygen	0.00
Nitrogen	0.00
Sulfur	0.00
Chlorine	0.00
Fluorine	0.00
NO	0.00
SO ₂	0.00
All organics	0.02
Inorganics	
Water	0.00
Glass-forming inerts	0.00
Bulk nontoxic metal	0.00
Arsenic (As)	0.00
Barium (Ba)	0.00
Beryllium (Be)	0.00
Cadmium (Cd)	0.00
Chromium (Cr)	0.00
Lead (Pb)	99.98
Mercury (Hg)	0.00
Selenium (Se)	0.00
Silver (Ag)	0.00
Tantalum (Ta)	0.00
Uranium (U)	0.00
All inorganics	99.98
<u>All organics and inorganic</u>	<u>100.00</u>

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993 in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Table 3-4. Elemental composition of DOE contact-handled MLLW assigned to metal melting and metal decontamination in the ITTS study.

Waste component	Mass %
Organics	
Carbon	0.00
Hydrogen	0.00
Oxygen	0.00
Nitrogen	0.00
Sulfur	0.00
Chlorine	0.00
Fluorine	0.00
NO	0.00
SO ₂	0.00
All organics	0.00
Inorganics	
Water	0.00
Glass-forming inerts	0.00
Bulk nontoxic metal	99.51
Arsenic (As)	0.00
Barium (Ba)	0.40
Beryllium (Be)	0.00
Cadmium (Cd)	0.09
Chromium (Cr)	0.00
Lead (Pb)	0.00
Mercury (Hg)	0.00
Selenium (Se)	0.00
Silver (Ag)	0.00
Tantalum (Ta)	0.00
Uranium (U)	0.00
All inorganics	100.00
All organics and inorganic	100.00

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993 in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Table 3-5. Elemental composition of DOE contact-handled MLLW assigned to special waste treatment in the ITTS study.

Waste component	Mass %
Organics	
Carbon	0.02
Hydrogen	0.01
Oxygen	33.29
Nitrogen	0.00
Sulfur	0.03
Chlorine	0.00
Fluorine	0.00
NO	0.00
SO ₂	0.00
All organics	33.34
Inorganics	
Water	3.75
Glass-forming inerts	1.04
Bulk nontoxic metal	0.02
Arsenic (As)	0.00
Barium (Ba)	0.00
Beryllium (Be)	14.14
Cadmium (Cd)	0.00
Chromium (Cr)	0.00
Lead (Pb)	1.95
Mercury (Hg)	0.00
Selenium (Se)	0.00
Silver (Ag)	0.00
Tantalum (Ta)	45.32
Uranium (U)	0.43
All inorganics	66.66
<u>All organics and inorganic</u>	<u>100.00</u>

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993 in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Table 3-6. Elemental composition of DOE contact-handled MLLW assigned to mercury recovery in the ITTS study.

Waste component	Mass %
Organics	
Carbon	0.00
Hydrogen	0.00
Oxygen	0.00
Nitrogen	0.00
Sulfur	0.00
Chlorine	0.00
Fluorine	0.00
NO	0.00
SO2	0.00
All organics	0.00
Inorganics	
Water	0.00
Glass-forming inerts	0.00
Bulk nontoxic metal	0.00
Arsenic (As)	0.00
Barium (Ba)	0.00
Beryllium (Be)	0.00
Cadmium (Cd)	0.00
Chromium (Cr)	0.00
Lead (Pb)	0.00
Mercury (Hg)	100.00
Selenium (Se)	0.00
Silver (Ag)	0.00
Tantalum (Ta)	0.00
Uranium (U)	0.00
All inorganics	100.00
<u>All organics and inorganic</u>	<u>100.00</u>

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993 in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Table 3-7. Elemental composition of DOE contact-handled MLLW assigned to aqueous waste treatment in the ITTS study.

Waste component	Mass %
Organics	
Carbon	0.26
Hydrogen	0.12
Oxygen	4.63
Nitrogen	1.35
Sulfur	0.00
Chlorine	0.20
Fluorine	0.00
NO	0.00
SO ₂	0.00
All organics	6.56
Inorganics	
Water	89.63
Glass-forming inerts	0.00
Bulk nontoxic metal	0.00
Arsenic (As)	0.15
Barium (Ba)	0.08
Beryllium (Be)	0.00
Cadmium (Cd)	1.14
Chromium (Cr)	1.52
Lead (Pb)	0.38
Mercury (Hg)	0.38
Selenium (Se)	0.08
Silver (Ag)	0.08
Tantalum (Ta)	0.00
Uranium (U)	0.00
All inorganics	93.44
<u>All organics and inorganic</u>	<u>100.00</u>

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993 in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Table 3-8. Elemental composition of DOE contact-handled MLLW assigned to polymer stabilization in the ITTS study.

Waste component	Mass %
Organics	
Carbon	0.00
Hydrogen	0.00
Oxygen	0.00
Nitrogen	0.00
Sulfur	0.00
Chlorine	61.38
Fluorine	0.00
NO	0.00
SO ₂	0.19
All organics	61.57
Inorganics	
Water	0.00
Glass-forming inerts	38.43
Bulk nontoxic metal	0.00
Arsenic (As)	0.00
Barium (Ba)	0.00
Beryllium (Be)	0.00
Cadmium (Cd)	0.00
Chromium (Cr)	0.00
Lead (Pb)	0.00
Mercury (Hg)	0.00
Selenium (Se)	0.00
Silver (Ag)	0.00
Tantalum (Ta)	0.00
Uranium (U)	0.00
All inorganics	38.43
All organics and inorganic	100.00

Source of data: compositional percentage breakdowns in SAIC informal report, v. 1, Table 2.2, dated February 1993 in conjunction with SAIC informal report elemental breakdown, dated April 8, 1994.

Table 3-9. Input feed rates for nineteen systems (lb/hr).

Subsystem		A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
	Rotary kiln, air		Rotary oxygen kiln	Rotary wet APC kiln, air	Rotary kiln, CO ₂ retention	Rotary kiln, air, polymer stabilization	Rotary maximum recycling	Slagging rotary kiln	Indirectly heated pyrolyzer	Plasma furnace	Plasma furnace, CO ₂ retention	Plasma gasification	Fixed hearth pyrolyzer, CO ₂ retention	Rotary kiln, air, thermal desorption	Molten salt oxidation	Molten Waste Destruction	Steam gasification	Isolc-heated vitrification	Thermal desorption and MEO	Thermal desorption and SVO
Administration (a)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Receiving and Preparation	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927
Sorting	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,190	2,927	1,500	1,190	1,190	2,927	2,080	2,070		2,120	1,540	2,250	2,250
Metal decontamination	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	-	468	468	468	468
Metal melting	149	149	149	149	149	149	149	-	149	-	-	-	149	149	149	149	149	149	149	149
Lead recovery	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
Main thermal treatment	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,149	2,000	2,149	2,149	2,149	2,000	660	2,000	2,617	2,000	2,000	2,000	2,000
Thermal Desorption	21,420	8,448	21,452	28,241	21,589	21,423	27,561	2,397	7,339	3,039	1,159	1,340								
Air pollution control	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
Aqueous waste treatment (b)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Organic liquid waste treatment	1,518	1,518	1,132	1,518	-	1,508	-	-	-	-	-	-	1,519	184	1,523		1,516			
Primary stabilization	595	595	1,981	460	1,673	30,24	595	595	595	259	595	245	492	282	595	120	595	595	334	119
Secondary stabilization (c, d)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Grout stabilization	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153
Special waste	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Mercury amalgamation	2,546	2,546	2,714	3,180	3,183	2,310	2,584	2,546	2,513	2,745	2,515	2,751	4,319	2,629	2,425	2,544	2,521	5,699	5,535	5,535
Certification and shipping	2,546	2,546	2,714	3,180	3,183	2,310	2,584	2,546	2,513	2,745	2,515	2,751	4,319	2,629	2,425	2,544	2,521	5,699	5,535	5,535

a. The input feed rate is not applicable to the administration subsystem.
b. The aqueous waste feed rate shown above only accounts for primary feed stream from receiving and shipping and does not account for secondary aqueous waste streams and recycle streams which varies on a system by system basis.
c. The feed to secondary stabilization is comprised of concentrated sludge from aqueous waste treatment, trace metals and spent lime from APC, sludge containing surface metal grit from metal decontamination and sulfate salts from receiving and shipping, concentrated liquids from SCWO, and solids from MEO.
d. The sludge waste input to secondary stabilization from aqueous waste treatment is 20% salts and solids by weight. In the case of system A-4, C-2, and D-1 10% of the used lime is routed to polymer stabilization.

Table 3-10. Energy consumption and costs for nineteen systems.

Unit prices:		Gas = \$2.00 /MMBtu,		Electricity = \$0.05 /kW-hr					
Sys.	Unit	Gas/ Elec.	Unit Heat Duty (Btu/hr)	Eff.	Total Heat Duty (Btu/hr)	Note Ref.	Energy Costs (\$/hr)		20-Year Costs (MM\$)
							Unit	Total	
A-1	KILN	G	0	1		g,p	0.00		
	SCC	G	8.99E+06	1		g	17.97		
	VITRIFIER	E	1.49E+06	0.8		h	27.30		
	MELTER	E	1.20E+05	0.85	1.10E+07	k	2.06	47.33	3.82
A-2	KILN	G	0	1		g,p	0.00		
	SCC	G	2.95E+06	1		g	5.89		
	VITRIFIER	E	1.49E+06	0.8		h	27.30		
	MELTER	E	1.20E+05	0.85	4.95E+06	k	2.06	35.25	2.84
A-3	KILN	G	0	1		g,p	0.00		
	SCC	G	9.01E+06	1		g	18.02		
	VITRIFIER	E	1.12E+06	0.8		h	20.43		
	MELTER	E	1.20E+05	0.85	1.05E+07	k	2.06	40.50	3.27
A-4	KILN	G	5.61E+06	1		g	11.22		
	SCC	G	7.63E+06	1		g	15.27		
	CO2-ABS	G	8.52E+06	0.8		c	21.31		
	CALCINER	G	5.76E+06	0.8		c	14.39		
	VITRIFIER	E	1.49E+06	0.8		h	27.30		
	MELTER	E	1.20E+05	0.85	3.31E+07	k	2.06	91.54	7.38
A-5	KILN	G	0	1		g,p	0.00		
	SCC	G	9.12E+06	1		g	18.23		
	MELTER	E	1.20E+05	0.85	9.26E+06	k	2.06	20.29	1.64
A-6	KILN	G	0	1		g,p	0.00		
	SCC	G	8.99E+06	1		g	17.97		

Table 3-10. (continued).

Unit prices:		Gas =	\$2.00 /MMBtu,		Electricity =	\$0.05 /kW-hr			
Sys.	Unit	Gas/ Elec.	Unit	Eff.	Total	Note Ref.	Energy Costs (\$/hr)		20-Year
			Heat Duty (Btu/hr)		Heat Duty (Btu/hr)		Unit	Total	Costs (MM\$)
	VITRIFIER	E	1.49E+06	0.8		h	27.30		
	SPLITTER	E	1.24E+07	0.5		n	362.18		
	MELTER	E	1.20E+05	0.85	3.57E+07	k	2.06	409.52	33.02
A-7	KILN	G	1.22E+07	1		g	24.42		
	SCC	G	4.47E+06	1	1.67E+07	g	8.94	33.37	2.69
B-1	PYROLYZER	G	0						
	VITRIFIER	E	2.57E+06	0.8		h	47.06		
	MELTER	E	1.20E+05	0.85	3.35E+06	k	2.06	49.12	3.96
C-1	PLASMA	E	2.93E+06	0.35		d	122.76		
	SCC	E	9.75E+05	0.35	1.12E+07	d	40.78	163.55	13.19
C-2	PLASMA	E	2.93E+06	0.35		d	122.74		
	SCC	G	7.74E+05	1		g	1.55		
	CO2-ABS	G	0.00E+00	0.8			0.00		
	CALCINER	G	2.66E+06	0.8	1.25E+07	c	6.64	130.93	10.56
								0.00	
C-3	GASIFIER	E	5.22E+06	0.35		d	218.31		
	STEAM GEN	E	6.89E+04	1	1.50E+07	j	1.01	219.31	17.69
								0.00	
D-1	PYROLYZER	G	0	1		g	0.00		
	SCC	G	0	1		g	0.00		
	CO2-ABS	G	2.08E+06	0.8		c	5.20		
	CALCINER	G	2.44E+06	0.8		c	6.11		
	VITRIFIER	E	2.57E+06	0.8		h	47.08		
	MELTER	E	1.20E+05	0.85	9.01E+06	k	2.06	60.45	4.87

Table 3-10. (continued).

Unit prices:		Gas =	\$2.00 /MMBtu,		Electricity =		\$0.05 /kW-hr		20-Year		
Sys.	Unit	Gas/ Elec.	Unit		Eff.	Heat Duty (Btu/hr)	Heat Duty (Btu/hr)	Note Ref.	Energy Costs (\$/hr)		Costs (MM\$)
			Heat Duty (Btu/hr)						Unit	Total	
E-1	KILN	G	0	1				g	0.00		
	SCC	G	9.18E+06	1				g	18.36		
	VITRIFIER	E	1.56E+05	0.8				h	2.86		
	DESORBER	G	9.89E+05	0.5				m	3.96		
	MELTER	E	1.20E+05	0.85		1.15E+07		k	2.06	25.17	2.03
F-1	MSO	E	0	1					0.00		
	VITRIFIER	E	2.34E+06	0.8				h	42.87		
	SCC	G	5.16E+05	1				g	1.03		
	MELTER	E	1.20E+05	0.85		3.58E+06		k	2.06	45.96	3.71
G-1	MELTER	E	5.14E+06	0.35		1.47E+07		o	215.08	215.08	17.34
H-1	GASIFIER	G	3.33E+06	1				e	6.67		
	VITRIFIER	E	2.18E+06	0.8				h	39.85		
	SCC	G	5.81E+05	1				g	1.16		
	MELTER	E	1.20E+05	0.85				k	2.06		
	REHEATER	E	4.63E+04	1		6.82E+06		j	0.68	50.42	4.07
J-1	VITRIFIER	E	2.72E+06	0.8				f	49.86		
	SCC	G	1.72E+06	1				g	3.44		
	MELTER	E	1.20E+05	0.85		5.26E+06		k	2.06	55.36	4.46
K-1	MEO	E	1.00E+06	0.5				i	29.38		
	DESORBER	G	7.43E+05	0.5				c,m	2.97		
	MELTER	E	1.20E+05	0.85		3.63E+06		k	2.06	34.42	2.78
										0.00	

Table 3-10. (continued).

Unit prices:		Gas = \$2.00 /MMBtu,		Electricity = \$0.05 /kW-hr					
Sys.	Unit	Gas/	Unit	Eff.	Total	Note	Energy Costs (\$/hr)		20-Year Costs (MM\$)
		Elec.	Heat Duty (Btu/hr)		Heat Duty (Btu/hr)		Unit	Total	
L-1	SCWO	E	0	1			0.00		
	PUMP	E	2.48E+06	0.9		a	40.38		
	DESORBER	G	7.43E+05	0.5		c,m	2.97		
	COMPRESSOR	E	1.02E+05	0.66		b	2.26		
	MELTER	E	1.20E+05	0.85		k	2.06		
	EVAPORATOR	G	3.12E+06	0.8	8.44E+06	c	7.81	55.48	4.47

- a - Mark's Standard Handbook for Mechanical Engineers, 8th Ed., p. 14-8
mechanical efficiency of about 0.90
- b - Engineering Evaluation of Energy Systems, Arthur Fraas, p. 319, .
compressor efficiencies of 0.73-0.86. Lower value used because of
high compression ratio, multiplied by mechanical efficiency of 0.90.
- c - Modeled in ASPEN without regard to type of power input. Duty
converted to lb CH₄/hr by dividing by 21500 BTU/lb, efficiency of 0.8
- d - Plasma unit thermal efficiency assumed to be 0.35
(telecon R. Eschenbach RETEC 2/3/95,
efficiency for transfered plasma using diatomic gas 0.30-0.40
- e - pulse combustor/heat transfer thermal efficiency of 0.90 assumed
- f - According to Teledyne-Brown Engineering, 750 kWh is required per ton
of glass produced (1280 BTU/lb). ASPEN PLUS calculates 1820 BTU/lb,
which would result in an efficiency of >1. Thermal efficiency of 0.8 assumed.
- g - Heat losses included in ASPEN model as 5% of sensible heat.
- h - Assumed same efficiency as Joule-heated METAL MELTER, 0.80.
- i - "Mediated Electrochemical Oxidation Treatment for Rocky Flats
Combustible Low-Level Mixed Waste," UCRL-ID-112283, March 1993
Z. Chiba (510-422-6124), coulombic efficiency of 45-55% at 50-70 C.
- j - Efficiency of 1.0 assumed for electric steam generator.

Table 3-10. (continued).

Unit prices:		Gas =		\$2.00 /MMBtu,		Electricity =		\$0.05 /kW-hr		
			Unit		Total					20-Year
		Gas/	Heat Duty		Heat Duty	Note	Energy Costs (\$/hr)			Costs
Sys.	Unit	Elec.	(Btu/hr)	Eff.	(Btu/hr)	Ref.	Unit	Total		(MM\$)
k	Mark's Standard Handbook for Mechanical Engineers, 8th Ed., p. 7-64 thermal efficiency of about 0.85 for 3 phase arc furnaces									
l	"Chemical Process Industries," R. Norris Shreeve, 5th Edition, McGraw- p. 167-170, lime manufacture requires 4.25 MMBTU/ton, rotary kiln uses 8.5 MMBTU/ton, or approximately 50% thermal efficiency.									
m	indirectly heated desorber, assumed thermal efficiency of 0.50									
n	assumed same efficiency as MEO, 0.5									
o	personal communication with Brian Payea, MMT, February 8. 1995									
p	Cooling water required to maintain temperature.									

Table 3-11. Offgas outputs from the nineteen systems (lb/hr).

	Rotary kiln, air	Rotary kiln, oxygen	Rotary kiln, air, wet APC	Rotary kiln, O ₂ , CO ₂ retention	Rotary kiln, air, polymer stabilization	Rotary kiln, air, maximum recycling	Slagging rotary kiln	Indirectly heated pyrolyzer	Plasma furnace	Plasma furnace, CO ₂ retention
Subsystem	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2
Main thermal treatment APC	20,200	5,377	20,252	6,127	20,317	20,242	26,304	1,433	6,762	1,836
Metal melting	46	46	46	46	46	46		46	-	-
Lead recovery	35	35	35	35	35	35	35	35	35	35
Mercury amalgamation	97	97	97	97	97	97	97	97	97	97
Primary stabilization	319	319	238	319	-	317	-	-	-	-
Total	20,697	5,874	20,668	6,624	20,495	20,737	26,436	1,611	6,894	1,968

	Plasma gasification	Fixed hearth pyrolyzer, CO ₂ retention	Rotary kiln, air, thermal desorption	Molten salt oxidation	Molten Metal Waste Destruction	Steam gasification	Joule-heated vitrification	Thermal desorption and MEO	Thermal desorption and SCWO
Subsystem	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
Main thermal treatment APC	11,891	1,822	6,645	7,194	11,451	7,429	3,197	3,409	617
Metal melting	-	46	46	46	-	46	46	46	46
Lead recovery	35	35	35	35	35	35	35	35	35
Mercury amalgamation	97	97	97	97	97	97	97	97	97
Primary stabilization	-		549	4544	-	754	-	-	-
Total	12,023	2,000	7,372	11,916	11,583	8,361	3,375	3,587	795

Note:

a. Offgases from indirectly heated combustion processes not included. Systems A-4, C-2, D-1, H-1, K-1 and C-1 have indirect heating.

Table 3-12. Waste volume reduction for the nineteen systems (ft³/hr).

	Rotary kiln, air	Rotary kiln, oxygen	Rotary kiln, air, wet APC	Rotary kiln, O ₂ , CO ₂ retention	Rotary kiln, air, polymer stabilization	Rotary kiln, air, maximum recycling	Slagging rotary kiln	Indirectly heated pyrolyzer	Plasma furnace	Plasma furnace, CO ₂ retention
Subsystem	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2
Main thermal treatment (ft ³ /hr)	-	-	-	-	-	-	9.0	8.0	7.8	7.8
Primary stabilization (ft ³ /hr)										
Source: Main thermal treatment	7.99	7.99	5.93	7.99	-	7.94	-	-	-	-
Source: Metal melting	0.12	0.12	0.12	0.12	0.12	0.12		0.12		
Source: Lead recovery	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Grout stabilization (ft ³ /hr)										
Source: Main thermal treatment	-	-	-	-	-	-	-	-	-	-
Source: Lead recovery	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Source: Mercury amalgamation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Polymer stabilization (ft ³ /hr)										
Source: Aqueous waste treatment, unprocessed Halide and Sulfate salts, trace metals from main thermal treatment APC, salts and solids from MSO and MEO.	2.95	2.95	8.41	9.02	25.89	0.13	2.95	2.95	2.95	4.85
Source: Metal decontamination	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Special waste treatment (ft ³ /hr)	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Total system output to disposal (ft ³ /hr)	13.59	13.6	17.0	19.7	28.5	10.7	14.5	13.6	13.2	15.1
Stabilized waste output to disposal from main thermal treatment and APC subsystems	10.9	10.9	14.3	17.0	25.9	8.0	12.0	10.9	10.7	12.6
Total system input for 20 years (1000ft ³) [same for all systems]	3,688	3,688	3,688	3,688	3,688	3,688	3,688	3,688	3,688	3,688
Total system output for 20 years (1000ft ³)	1,096	1,096	1,369	1,585	2,301	864	1,170	1,096	1,067	1,220
Volume reduction factor (Input volume /Output volume)	3.37	3.37	2.69	2.33	1.60	4.27	3.15	3.37	3.46	3.02

Table 3-12. Continued.

	Plasma gasification	Fixed hearth pyrolyzer, CO2 retention	Rotary kiln, air, thermal desorption	Molten salt oxidation	Molten Metal Waste Destruction	Steam gasification	Joule-heated vitrification	Thermal desorption and MEO	Thermal desorption and SCWO
Subsystem	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
Main thermal treatment (ft ³ /hr)	7.8	-	-	-	8.4	-	8.0	-	-
Primary stabilization (ft ³ /hr)									
Source: Main thermal treatment	-	8.00	0.86	8.02	-	7.98	-	-	-
Source: Metal melting		0.12	0.12	0.12		0.12	0.12	0.12	0.12
Source: Lead recovery	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Grout stabilization (ft ³ /hr)									
Source: Main thermal treatment	-	-	24.91	-	-	-	-	36.73	36.73
Source: Lead recovery	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Source: Mercury amalgamation	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Polymer stabilization (ft ³ /hr)									
Source: Aqueous waste treatment, unprocessed Halide and Sulfate salts, trace metals from main thermal treatment APC, salts and solids from MSO and MEO.	2.95	4.56	2.38	3.93	0.70	2.95	2.95	3.23	1.18
Source: Metal decontamination	0.11	0.11	0.11	0.11		0.11	0.11	0.11	0.11
Special waste treatment (ft ³ /hr)	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Total system output to disposal (ft³/hr)	13.2	15.2	30.8	14.6	11.5	13.6	13.6	42.6	40.5
Stabilized waste output to disposal from main thermal treatment and APC subsystems	10.7	12.5	28.1	11.9	9.1	10.9	10.9	39.9	37.9
Total system input for 20 years (1000ft ³) [same for all systems]	3,688	3,688	3,688	3,688	3,688	3,688	3,688	3,688	3,688
Total system output for 20 years (1000ft ³)	1,067	1,226	2,482	1,176	929	1,095	1,095	3,435	3,270
Volume reduction factor (Input volume /Output volume)	3.46	3.01	1.49	3.13	3.97	3.37	3.37	1.07	1.13

Notes:

1. This table shows the waste outputs from the 19 systems. The waste output sent to shipping and certification originates from the main thermal treatment system (for some systems), the grout and polymer stabilization subsystems and the special waste subsystem. The output does not include recyclables that will not be disposed, such as cast metal from thermal treatment processes, metal melting, decontaminated lead and other decontaminated metals from metal decontamination.
2. The total system output to disposal is rounded to one decimal point.
3. Slag density from relevant main thermal treatment systems is assumed to be the same as the vitrified slag density of 187 lb/ft³. Metal slag is assumed to have the density of steel.
4. The input to polymer stabilization for system F-1 also includes rejected sodium carbonate salt and acid salts such as sodium chloride. The input to polymer stabilization for system K-1 includes precipitated solids from the MEO electrolyte waste stream.
5. The total input mass to the integrated facility was calculated by using a total input mass flow rate of 2,927 lb/hr operating 4032 hours per year for 20 years.
6. Total input volume to the integrated facility was calculated using a weight-average density of 64 lb/ft³. This weighted average density was calculated using the densities and mass quantities presented in Table 3.3 of the formal report, Integrated Thermal Treatment System (ITTS) Study Quantities and Characteristics of the Contact-Handled LWR Systems for DOE complex and its Sites, vol 1, February 1993.

Percentage of input waste treated by treatment technology.

Figure 3-1. Percentage of input waste treated by main thermal treatment technology as a percentage of total waste input to the ITTS facility.

Figure 3-2. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, air (System A-1).

Figure 3-3. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, oxygen (System A-2).

Figure 3-4. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, air, wet APC (System A-3).

Figure 3-5. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, oxygen, CO₂ retention (System A-4).

Figure 3-6. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, air, polymer stabilization (System A).

Figure 3-7. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, air, maximum recycling (System A-6).

NOTES:

A. MASS AND VOLUME FLOW RATES FOR OTHER SUBSYSTEMS ARE NOT SHOWN ABOVE. FOR MORE DETAIL ON THE TOTAL WASTE OUTPUT TO DISPOSAL, REFER TO TABLE 3-12 IN THIS REPORT.

B. WATER CONTENT NOT INCLUDED.

Figure 3-8. General mass flow rates (lb/hr) for the main thermal treatment and APC for the slagging rotary kiln (System A-7).

NOTES:

A. MASS AND VOLUME FLOW RATES FOR OTHER SUBSYSTEMS ARE NOT SHOWN ABOVE. FOR MORE DETAIL ON THE TOTAL WASTE OUTPUT TO DISPOSAL, REFER TO TABLE 3-12 IN THIS REPORT.

B. WATER CONTENT NOT INCLUDED.

Figure 3-9. General mass flow rates (lb/hr) for the main thermal treatment and APC for the indirectly heated pyrolyzer (System B-1).

NOTES:

A. MASS AND VOLUME FLOW RATES FOR OTHER SUBSYSTEMS ARE NOT SHOWN ABOVE. FOR MORE DETAIL ON THE TOTAL WASTE OUTPUT TO DISPOSAL, REFER TO TABLE 3-12 IN THIS REPORT.

B. WATER CONTENT NOT INCLUDED.

Figure 3-10. General mass flow rates (lb/hr) for the main thermal treatment and APC for the plasma furnace (System C-1).

Figure 3-11. General mass flow rates (lb/hr) for the main thermal treatment and APC for the plasma furnace, CO₂ retention (System C-2).

Figure 3-12. General mass flow rates (lb/hr) for the main thermal treatment and APC for the plasma gasification (System C-3).

Figure 3-13. General mass flow rates (lb/hr) for the main thermal treatment and APC for the fixed hearth pyrolyzer, CO₂ retention (System D-1).

Figure 3-14. General mass flow rates (lb/hr) for the main thermal treatment and APC for the rotary kiln, air, thermal desorption (System E-1).

Figure 3-15. General mass flow rates (lb/hr) for the main thermal treatment and APC for the molten salt oxidation (System F-1).

Figure 3-16. General mass flow rates (lb/hr) for the main thermal treatment and APC for the molten metal waste destruction (System G-1).

Figure 3-17. General mass flow rates (lb/hr) for the main thermal treatment and APC for the steam gasification (System H-1).

NOTES:
 A. MASS AND VOLUME FLOW RATES FOR OTHER SUBSYSTEMS ARE NOT SHOWN ABOVE. FOR MORE DETAIL ON THE TOTAL WASTE OUTPUT TO DISPOSAL, REFER TO TABLE 3-12 IN THIS REPORT.
 B. WATER CONTENT NOT INCLUDED.

Figure 3-18. General mass flow rates (lb/hr) for the main thermal treatment and APC for the joule-heated vitrification (System J-1).

Figure 3-19. General mass flow rates (lb/hr) for the main thermal treatment and APC for the thermal desorption and mediated electrochemical oxidation (System K-1).

Figure 3-20. General mass flow rates (lb/hr) for the main thermal treatment and APC for the thermal desorption with supercritical water oxidation (System L-1).

Figure 3-21. General mass flow rates (lb/hr) for metal melting subsystem.

Figure 3-22. General mass flow rates (lb/hr) for metal decontamination subsystem.

Figure 3-23. General mass flow rates (lb/hr) for lead recovery subsystem.

AQUEOUS WASTE TREATMENT SUBSYSTEM

OTHER SUBSYSTEMS

Waste Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Aqueous Wastes 1% TOC	10.0	0.0	0.0	0.0	0.0	3.0	9.9	0.0	0.0	0.0	0.0	6.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Aqueous Wastes 100 ppm TDS, 10000ppm TSS	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aqueous Wastes 10000 ppm TDS, 1000 ppm TSS	0.0	0.0	60.0	0.0	0.0	3.0	0.0	0.1	59.9	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.2	0.0
Aqueous Wastes 200 ppm Hg, 1000 ppm TSS	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Scrubber Salts	0.0	0.0	0.0	0.0	13474.0	0.0	0.0	0.0	0.0	565.0	12909.0	0.0	0.0	0.0	226.0	113.0	0.0	0.0	452.0
Total	10.0	8.0	60.0	2.0	13474.0	6.0	9.9	0.1	69.9	565.0	12909.0	6.0	0.1	0.1	226.0	113.0	0.1	0.2	452.0

Note 1. The above mass balance is for primary waste input only except for APC scrubber liquor stream shown above.

Note 2. The scrubber liquor mass balance above has been shown for system A-1 only.

3-24. General mass flow rates (lb/hr) for aqueous waste treat subsystem.

Figure 3-25. General mass flow rates (lb/hr) for mercury amalgamation subsystem.

4. PLANNING LIFE-CYCLE COST ESTIMATES AND SENSITIVITY ANALYSIS

This section summarizes the PLCC estimates for the nineteen treatment systems. PLCC estimates include both treatment and disposal costs. Transportation costs have been included on a generic basis in Section 4.9. Cost studies have found that transportation costs are a small fraction (approximately 5%) of the total life-cycle costs.

Treatment systems reviewed in Phase 2 are sized at a nominal capacity (as described in Section 3) of 2,927 lb/hr to allow for direct comparison. It is assumed that the facility will process most of the stored alpha and nonalpha MLLW in a 20-year period. For smaller systems, the cost versus capacity curves from the Waste Management Facilities Cost Information Report¹ should be used.

Since one system is used for the entire inventory, the facility is designed for alpha waste. PLCC estimates presented in this section are based on a facility that includes a stringent alpha radiation confinement design. The alternative is to provide two facilities, one for alpha and one for nonalpha MLLW.

4.1 Estimating Methods, Basis, and Assumptions

Figure 4-1 (page 4-32) shows the steps used in the cost estimating approach. Cost information in this report was obtained during the 2nd and 3rd quarters of 1994. The information is based on the currently available knowledge about waste processing requirements, technology availability, and cost data. The information may have to be updated when additional knowledge is gained in these areas. All facilities are assumed to be government owned and contractor operated. Thus, cost multipliers appropriate to this business relationship are used.

The PLCC estimates are based on the assumption that the operating life of the facility is 20 years, which is equal to 80,640 total operating hours. The treatment unit rates are obtained by dividing the total PLCC estimate by the total operating hours per year. The PLCC cost estimates represent one system handling 236 million pounds of waste over 20 years. To get a rough estimate of the total costs for treating DOE waste now in inventory, the unit rates could be multiplied by the total mass in the inventory.

4.2 Treatment Facility PLCC Estimate Summaries

The PLCC estimate for each facility is divided into six components (see Figure 4-1). Each was estimated separately. A summary of the PLCC estimates for the nine systems is presented in Table 4-1 (page 4-7). Discussions of the six cost components are presented below.

4.2.1 Studies and Bench-Scale Tests and Demonstration

Costs for the first and second cost components (studies and bench-scale tests, and demonstration) are obtained by estimating the cost of research manpower, equipment, and facility needs.

4.2.2 Facility Capital Costs

The third cost component, production facility construction costs (also referred to as facility capital cost or "line-item" cost), consists of five key subcomponents, which are described below. A breakdown of the construction cost per subsystem for the baseline system (System A-1) is presented in Figure 4-2. Life-cycle costs for subsystems in the baseline system are shown in Figure 4-3. The unit rate cost estimates for the subsystems of the baseline system are shown in Figure 4-4.

4.2.2.1 Design. The design subcomponent includes Title 1, or preliminary design, and Title 2, or detailed design. Design is estimated at 25% of facility construction cost for an alpha facility.

4.2.2.2 Inspection. The inspection subcomponent includes Title 3, or engineering support, during construction. Inspection is estimated at 7% of the facility construction cost.

4.2.2.3 Project management. The project management subcomponent includes project management costs incurred both by DOE and the site management and operations (M&O) contractor. Project management is estimated at 10% of facility construction cost.

4.2.2.4 Construction cost. Facility construction cost estimates are developed from a preconceptual design package developed for the subsystems and the integrated facilities. The preconceptual design packages include a PFD with mass flow rates, a FAD, a scoping study layout (SSL), and a summary of F&ORs. Construction is divided into the following three parts:

- **Building and structures.** Building and structure costs are estimated by multiplying building unit costs by the space square footage allocated to each subsystem in the SSLs. Assumed unit rates are applied to several categories of buildings: \$1,700 per square foot for triple-confinement alpha cells (used for alpha waste processing areas); \$800 per square foot for double-confinement alpha cells (used for alpha equipment pull-out areas); \$800 per square foot for operating areas next to alpha cells; \$420 per square foot for packaged waste handling areas (truck bay or drum storage); \$420 per square foot for the process area for nonalpha waste; \$420 per square foot for the operator and packaged waste handling area for nonalpha waste; \$180 per square foot for office area; and \$420 per square foot for the analytical laboratory. Building unit rates include all material and labor needed for constructing the building shell including utilities; lighting; heating, ventilation, and air conditioning (HVAC); and site development costs. Site development costs assume that all utilities (power, sanitary and storm sewers, site communication, and alarms) and access roads are available within 100 feet from the outer walls of the treatment facility. Special steel supports, foundations, and ventilation ducts and hoods required by the process components are not included in the standard building unit rates. These rates include costs for imposing stringent DOE health and safety standards to facility construction.
- **Equipment.** Cost estimates for major equipment were obtained from a similar facility, by soliciting budgetary costs from suppliers, or by making engineering judgments. Cost for equipment installation is estimated based on individual requirements of the equipment.

Allowances for electrical, instrumentation, and mechanical bulks are estimated as a percentage of the total equipment purchase costs. Details are documented in the Phase 1 report.⁷

- **Indirect costs.** Indirect costs include subcontractor overhead and fee. This is estimated at 29% of the total of building, structure, and equipment costs.

4.2.2.5 Construction management. The construction management subcomponent is estimated at 17% of construction cost, which is the sum of the equipment, building, and indirect costs. Construction management includes material and services procurement and control activities, which are usually handled by the site construction management (CM) contractor. Allowances for project scope change or management reserve are estimated at 10% of construction costs.

Because the costs are a planning-level estimate, a 25% contingency is included. The contingency is applied to the total of all components in the production facility construction cost.

4.2.3 Preconstruction and Preoperational Activities

The fourth cost component (operations budget funded activities) includes conceptual design, safety assurance, NEPA compliance efforts, permitting, preparation for operation, and project management costs. Conceptual design is estimated to be 1.5% of line-item (production facility construction) cost; the cost for safety assurance (safety analysis reports) is estimated at 1%. The costs for an environmental impact statement for NEPA compliance and for RCRA, TSCA, CAA, state, local and other permits are estimated at \$6 million. All other subcomponents of the cost of the operations budget funded activities, including preoperation readiness reviews, facility start-up, operator hiring and training costs, are assumed to be equal to 1 year of total facility operating costs.

4.2.4 Operating Cost

The fifth cost component, operations and maintenance (O&M), consists of five subcomponents: operating labor, utilities, consumable materials, maintenance parts and equipment, and maintenance labor costs. The first three subcomponents are estimated by analyzing the requirements of each facility at the subsystem level (see Tables 4-2 and 4-3 for administration and operations staffs for the baseline system).¹ The remaining two subcomponents are estimated as a percentage of the original equipment installed at the facility. Accordingly, the costs for annual maintenance spare parts and replacement equipment are estimated to be about 7% of the original equipment purchase cost. Maintenance labor is estimated to cost 250% of the cost of spare parts and replacement equipment on an annual basis.

4.2.5. Decontamination and Decommissioning

The sixth cost component, decontamination and decommissioning (D&D), is estimated by multiplying a D&D unit rate of \$450 per square foot by the square footage of the total facility.²

The total operating manpower compares well with data obtained during a telephone conversation with personnel from a commercial hazardous nonradioactive waste incineration facility in Utah.

4.2.6 Total System Processing PLCC Estimates

A histogram of cost estimates for all nineteen systems is presented in Figure 4-5. The total system life-cycle costs for the nineteen systems are presented in Table 4-4. A comparison of treatment life-cycle costs for the nineteen systems is presented in Table 4-5. Normalized system cost breakdown by subsystem is presented in Table 4-6, where system A-1 is used as the baseline for normalization.

Table 4-4 also presents the unit costs of treating incoming wastes, which are calculated by dividing the PLCC cost by the input waste volume over 20 years of operation. The unit cost of treating waste is presented two ways. In the first case, all systems are considered to treat 2927 lbs/hr of waste. In second case, the systems that use contaminated soil for vitrification are considered to treat 2927 lb/hr plus the added (contaminated) soil waste. This lowers the unit costs of systems designed to treat soil. Table 4-7 presents the treatment life-cycle cost estimate for each of the subsystems of the nineteen systems.

4.3 Disposal Cost Summaries

PLCC estimates for the disposal of waste from the nineteen systems are listed in Table 4-4 and shown in Figure 4-5. These estimates are based on a unit rate of \$243 per cubic foot for burial in an engineered (above-ground or below-ground vault) disposal facility. As shown, System A-6 (rotary kiln incineration with maximum recycling) has the lowest disposal cost, while System K-1 (thermal desorption with debris grouting plus MEO) has the highest.

A cost comparison of vitrification and grouting was performed. The cost of vitrification was based on the baseline system, A-1, which includes vitrification of ash discharged from the rotary kiln. The cost of grouting was based on System A-5 (rotary kiln, air, polymer stabilization), modified to perform ash stabilization by grouting. The total PLCC estimates for these two options as a function of disposal cost are presented graphically in Figure 4-6. In this analysis, no credit is given for treatment of contaminated soil.

At the assumed disposal cost of \$243/ft³, disposal of grout-stabilized waste (\$526.0 million) costs more than disposal of vitrified waste (\$231.2 million). If the disposal unit cost is reduced to \$58/ft³, the total life-cycle cost of the two alternatives will be equal. At disposal rates of less than \$58/ft³, grout stabilization becomes a cost-effective stabilization alternative compared to vitrification.

4.4 Sensitivity Analysis

The overall system PLCC estimates (processing and disposal) for the baseline system, A-1, have been analyzed for sensitivity against the system cost components and subcomponents. These factors include bench-scale testing and demonstration, building, equipment, operations budget funded activities, operations and maintenance, and decontamination and disposal costs. Sensitivity of the life-cycle costs is expressed in terms of the cost per pound of treating the input waste. The total cost for one facility is determined by multiplying the unit costs (\$/lb) by the assumed total quantity of the waste processed by the facility, which is 188,780,000 lbs. Results, shown in Figure 4-7, are discussed below.

- **Bench-scale testing and demonstration cost components.** The PLCC estimate has a low sensitivity to the variation in bench-scale testing and demonstration costs. Doubling this cost component will result in less than a 5% increase in the overall PLCC estimate.
- **Equipment cost subcomponent.** Doubling the equipment costs subcomponent will result in an increase of less than 15% in the overall PLCC estimate.
- **Building cost subcomponent.** Doubling the building costs subcomponents will result in an increase of about 10% in the overall PLCC estimate.
- **Operating budget funded cost component.** The PLCC estimate has a low sensitivity to variation in the operations budget funded cost component. Doubling this cost component will result in about a 5% increase in the overall PLCC estimate.
- **Operating and maintenance cost component.** The PLCC estimate is highly sensitive to the operations and maintenance cost component. Doubling the cost of operations and maintenance will result in a 65% increase in the overall PLCC estimate.
- **Decontamination and decommissioning cost component.** The PLCC estimate has a low sensitivity to the decontamination and decommissioning cost component. Doubling this cost will result in an increase of less than 5% in the overall PLCC estimate.
- **Disposal costs.** Doubling the base estimate cost of \$243/ft³ will increase the total life-cycle cost by about 11%.

4.5 Sensitivity Analysis of Technology Development State

System cost risks for less developed technologies have been included in the form of contingency allowances in the PLCC. Some systems have a higher level of uncertainty due to the state of development of the technology. These systems were assigned higher development and demonstration costs based on the estimated development necessary.

Preoperation costs also reflect the state of technology development. For commercially available systems, a wide experience base supports achieving quick resolution to startup problems, which will be primarily related to system integration and overall process engineering. For systems in a newer technology development state, greater problems at startup should be expected—process problems are more likely for components for which the experience base is laboratory trials, rather than years of operation. Systems were assigned a risk level based on the relative technology state of the system; these risk levels are shown in Table 4-8. Commercially available systems, such as the rotary kiln, were assigned the lowest risk (Level 1). These systems are assumed to be fully operational in 1 year. Systems for which some commercial experience exists but a higher operational risk is judged to exist, such as the indirectly heated pyrolyzer and steam gasification system, are assumed to be fully operational in two years (Level 2). Level 3 systems, judged to be higher risk, include the plasma furnace (C-1) and commercial systems with CO₂ retention; these are given three years before becoming fully operational. The highest risk level was assigned to the systems at the earliest stage of development, such as molten salt oxidation, molten metal waste destruction, and steam gasification.

Sensitivity analysis was then performed to consider the effect of technology development state by varying the preoperation cost contingency. Table 4-8 shows the results of this analysis.

As Table 4-8 shows, extending the preoperation period can be considered as a percentage increase to the total PLCC. Level 2 systems' costs are increased approximately 4%; Level 3 systems demonstrate about a 7% increase and Level 4, the highest risk systems, show an 11% increase in costs.

4.6 Economic Impact of Stabilization Technology

Cost analyses were performed to determine the sensitivity of the PLCC estimates to three different stabilization technologies: polymer solidification, cement solidification, and vitrification. The results (see Figure 4-8) show that the lowest life-cycle unit cost is for vitrification, about \$13/lb. The highest cost is for cement, about \$16/lb. The cost for polymer stabilization is about \$14/lb.

4.7 Economic Impact of Delisting

Economic analysis shows that delisting of the scrubber salts will reduce the cost by \$0.35 per pound of input waste. This is based on a conservative assumption that the delisted waste will be disposed in a shallow-land burial facility without stabilization. If the entire vitrified waste is disposed in a non-RCRA facility at a cost of \$100/ft³, then the overall savings could be about \$1/lb which is about 8% of the total life-cycle cost.

4.8 Transportation Cost

A rough estimate of transportation cost was performed to determine the magnitude of this cost component. The estimate is based on the following assumptions:

- About 60% of the waste is shipped to the treatment facility from other waste generators located 1,000 miles from the facility.
- The treated waste is disposed at the same location it is treated.
- The waste containers are contact handled, do not require a special over-pack, and are shipped in enclosed trailers.
- The waste has an average density of 35 lbs/ft³.
- The volume of waste transported in each shipment is 290 ft³.

Table 4-1. Planning life-cycle cost estimates for the ITTS study systems (in thousands of dollars).

Cost component	Cost Items	Cost (x 1000) System A-1 Rotary kiln, air
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$18,900
1.2 Equipment costs		\$2,200
1.3 Installation costs		\$1,100
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,220
1.5 Contingency	(25 % of 1.1 through 1.4)	\$6,105
Subtotal 1.0		\$30,525
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$7,740
2.3 Inspection cost	(7 % of 2.5)	\$1,806
2.4 Project management	(10 % of 2.5)	\$2,580
2.5 Construction cost		
2.5.1 Building structure costs		\$3,000
2.5.2 Equipment costs		\$17,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$5,800
Subtotal of 2.5		\$25,800
2.6 Construction management costs	(17 % of 2.5)	\$4,412
2.7 Management reserve	(10 % of 2.5)	\$2,580
2.8 Contingency	(25 % of 2.1 through 2.7)	\$13,929
Subtotal 2.0		\$69,647
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$66,353
3.2 Inspection cost	(7 % of 3.4)	\$18,579
3.3 Project management	(10 % of 3.4)	\$26,541
3.4 Construction cost		
3.4.1 Building structure costs		\$88,175
3.4.2 Equipment costs		\$117,570
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$59,666
Subtotal of 3.4		\$265,411
3.5 Construction management	(17 % of 3.4)	\$45,385
3.6 Management reserve	(10 % of 3.4)	\$26,541
3.7 Contingency	(25 % of 3.1 through 3.5)	\$105,567
Subtotal 3.0		\$554,377
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$8,316
4.2 Safety assurance	(1 % of 3.0)	\$5,544
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$68,093
4.5 Project management	(10 % of 4.1 through 4.4)	\$8,795
Subtotal 4.0		\$96,747
Total initial cost (1.0,2.0,3.0 & 4.0)		\$751,297
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$36,400
5.2 Annual utility costs		\$836
5.3 Annual material costs		\$5,171
5.4 Annual maintenance costs		\$12,067
5.5 Contingency	(25 % of 5.1 through 5.4)	\$13,619
5.6 Subtotal 5.0		\$68,093
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,361,850
6.0 Decontamination & decommissioning		\$54,171
7.0 ROM life cycle costs (20 years operation)		\$2,167,318
Storage O & M		\$408,626
Total ROM Life cycle costs		\$2,575,944

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System A-2 Rotary kiln, oxygen
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$18,900
1.2 Equipment costs		\$2,200
1.3 Installation costs		\$1,100
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,220
1.5 Contingency	(25 % of 1.1 through 1.4)	\$6,105
Subtotal 1.0		\$30,525
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$7,740
2.3 Inspection cost	(7 % of 2.5)	\$1,806
2.4 Project management	(10 % of 2.5)	\$2,580
2.5 Construction cost		
2.5.1 Building structure costs		\$3,000
2.5.2 Equipment costs		\$17,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$5,800
Subtotal of 2.5		\$25,800
2.6 Construction management costs	(17 % of 2.5)	\$4,412
2.7 Management reserve	(10 % of 2.5)	\$2,580
2.8 Contingency	(25 % of 2.1 through 2.7)	\$13,929
Subtotal 2.0		\$69,647
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$64,131
3.2 Inspection cost	(7 % of 3.4)	\$17,957
3.3 Project management	(10 % of 3.4)	\$25,653
3.4 Construction cost		
3.4.1 Building structure costs		\$86,975
3.4.2 Equipment costs		\$111,882
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$57,669
Subtotal of 3.4		\$256,526
3.5 Construction management	(17 % of 3.4)	\$43,866
3.6 Management reserve	(10 % of 3.4)	\$25,653
3.7 Contingency	(25 % of 3.1 through 3.5)	\$102,033
Subtotal 3.0		\$535,818
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$8,037
4.2 Safety assurance	(1 % of 3.0)	\$5,358
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$68,939
4.5 Project management	(10 % of 4.1 through 4.4)	\$8,833
Subtotal 4.0		\$97,168
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$733,158
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$36,400
5.2 Annual utility costs		\$806
5.3 Annual material costs		\$6,445
5.4 Annual maintenance costs		\$11,500
5.5 Contingency	(25 % of 5.1 through 5.4)	\$13,788
5.6 Subtotal 5.0		\$68,939
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,378,775
6.0 Decontamination & decommissioning		\$53,776
7.0 ROM life cycle costs (20 years operation)		\$2,165,709
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System A-3 Rotary kiln, air, wet APC
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$19,050
1.2 Equipment costs		\$2,200
1.3 Installation costs		\$1,100
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,235
1.5 Contingency	(25 % of 1.1 through 1.4)	\$6,146
Subtotal 1.0		\$30,731
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$7,160
2.3 Inspection cost	(7 % of 2.5)	\$1,671
2.4 Project management	(10 % of 2.5)	\$2,387
2.5 Construction cost		
2.5.1 Building structure costs		\$2,500
2.5.2 Equipment costs		\$16,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$5,365
Subtotal of 2.5		\$23,865
2.6 Construction management costs	(17 % of 2.5)	\$4,081
2.7 Management reserve	(10 % of 2.5)	\$2,387
2.8 Contingency	(25 % of 2.1 through 2.7)	\$13,087
Subtotal 2.0		\$65,436
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$64,918
3.2 Inspection cost	(7 % of 3.4)	\$18,177
3.3 Project management	(10 % of 3.4)	\$25,967
3.4 Construction cost		
3.4.1 Building structure costs		\$86,975
3.4.2 Equipment costs		\$114,320
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$58,376
Subtotal of 3.4		\$259,671
3.5 Construction management	(17 % of 3.4)	\$44,404
3.6 Management reserve	(10 % of 3.4)	\$25,967
3.7 Contingency	(25 % of 3.1 through 3.5)	\$103,284
Subtotal 3.0		\$542,387
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$8,136
4.2 Safety assurance	(1 % of 3.0)	\$5,424
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$67,764
4.5 Project management	(10 % of 4.1 through 4.4)	\$8,732
Subtotal 4.0		\$96,056
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$734,610
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$36,400
5.2 Annual utility costs		\$842
5.3 Annual material costs		\$5,213
5.4 Annual maintenance costs		\$11,756
5.5 Contingency	(25 % of 5.1 through 5.4)	\$13,553
5.6 Subtotal 5.0		\$67,764
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,355,275
6.0 Decontamination & decommissioning		\$53,776
7.0 ROM life cycle costs (20 years operation)		\$2,143,661
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System A-4 Rotary kiln, oxygen, CO ₂ retention
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$19,800
1.2 Equipment costs		\$2,400
1.3 Installation costs		\$1,600
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,380
1.5 Contingency	(25 % of 1.1 through 1.4)	\$6,545
Subtotal 1.0		\$32,725
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$10,062
2.3 Inspection cost	(7 % of 2.5)	\$2,348
2.4 Project management	(10 % of 2.5)	\$3,354
2.5 Construction cost		
2.5.1 Building structure costs		\$4,000
2.5.2 Equipment costs		\$22,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$7,540
Subtotal of 2.5		\$33,540
2.6 Construction management costs	(17 % of 2.5)	\$5,735
2.7 Management reserve	(10 % of 2.5)	\$3,354
2.8 Contingency	(25 % of 2.1 through 2.7)	\$17,298
Subtotal 2.0		\$86,491
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$66,729
3.2 Inspection cost	(7 % of 3.4)	\$18,684
3.3 Project management	(10 % of 3.4)	\$26,692
3.4 Construction cost		
3.4.1 Building structure costs		\$86,975
3.4.2 Equipment costs		\$119,938
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$60,005
Subtotal of 3.4		\$266,918
3.5 Construction management	(17 % of 3.4)	\$45,643
3.6 Management reserve	(10 % of 3.4)	\$26,692
3.7 Contingency	(25 % of 3.1 through 3.5)	\$106,167
Subtotal 3.0		\$557,524
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$8,363
4.2 Safety assurance	(1 % of 3.0)	\$5,575
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$72,501
4.5 Project management	(10 % of 4.1 through 4.4)	\$9,244
Subtotal 4.0		\$101,683
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$778,424
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$36,960
5.2 Annual utility costs		\$1,376
5.3 Annual material costs		\$7,335
5.4 Annual maintenance costs		\$12,330
5.5 Contingency	(25 % of 5.1 through 5.4)	\$14,500
5.6 Subtotal 5.0		\$72,501
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,450,025
6.0 Decontamination & decommissioning		\$53,776
7.0 ROM life cycle costs (20 years operation)		\$2,282,225
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System A-5 Rotary kiln, air, polymer stab.
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$16,050
1.2 Equipment costs		\$1,700
1.3 Installation costs		\$1,000
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$1,875
1.5 Contingency	(25 % of 1.1 through 1.4)	\$5,156
Subtotal 1.0		\$25,781
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$7,740
2.3 Inspection cost	(7 % of 2.5)	\$1,806
2.4 Project management	(10 % of 2.5)	\$2,580
2.5 Construction cost		
2.5.1 Building structure costs		\$3,000
2.5.2 Equipment costs		\$17,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$5,800
Subtotal of 2.5		\$25,800
2.6 Construction management costs	(17 % of 2.5)	\$4,412
2.7 Management reserve	(10 % of 2.5)	\$2,580
2.8 Contingency	(25 % of 2.1 through 2.7)	\$13,929
Subtotal 2.0		\$69,647
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$58,751
3.2 Inspection cost	(7 % of 3.4)	\$16,450
3.3 Project management	(10 % of 3.4)	\$23,500
3.4 Construction cost		
3.4.1 Building structure costs		\$82,471
3.4.2 Equipment costs		\$99,703
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$52,830
Subtotal of 3.4		\$235,004
3.5 Construction management	(17 % of 3.4)	\$40,186
3.6 Management reserve	(10 % of 3.4)	\$23,500
3.7 Contingency	(25 % of 3.1 through 3.5)	\$93,473
Subtotal 3.0		\$490,866
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$7,363
4.2 Safety assurance	(1 % of 3.0)	\$4,909
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$67,508
4.5 Project management	(10 % of 4.1 through 4.4)	\$8,578
Subtotal 4.0		\$94,357
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$680,651
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$37,520
5.2 Annual utility costs		\$789
5.3 Annual material costs		\$5,513
5.4 Annual maintenance costs		\$10,184
5.5 Contingency	(25 % of 5.1 through 5.4)	\$13,502
5.6 Subtotal 5.0		\$67,508
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,350,150
6.0 Decontamination & decommissioning		\$52,497
7.0 ROM life cycle costs (20 years operation)		\$2,083,298
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000)	
		System A-6 Rotary kiln, oxygen, max. recycling	
1.0 Studies and bench-scale test costs			
1.1 Manpower costs during research			\$20,550
1.2 Equipment costs			\$2,600
1.3 Installation costs			\$1,300
1.4 Project management before title 1	(10 % of 1.1 through 1.3)		\$2,445
1.5 Contingency	(25 % of 1.1 through 1.4)		\$6,724
Subtotal 1.0			\$33,619
2.0 Demonstration costs			
2.1 Manpower costs during demonstration			\$10,800
2.2 Design cost	(30 % of 2.5)		\$7,740
2.3 Inspection cost	(7 % of 2.5)		\$1,806
2.4 Project management	(10 % of 2.5)		\$2,580
2.5 Construction cost			
2.5.1 Building structure costs			\$3,000
2.5.2 Equipment costs			\$17,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)		\$5,800
Subtotal of 2.5			\$25,800
2.6 Construction management costs	(17 % of 2.5)		\$4,412
2.7 Management reserve	(10 % of 2.5)		\$2,580
2.8 Contingency	(25 % of 2.1 through 2.7)		\$13,929
Subtotal 2.0			\$69,647
3.0 Production facility construction costs			
3.1 Design cost	(25 % of 3.4)		\$68,134
3.2 Inspection cost	(7 % of 3.4)		\$19,078
3.3 Project management	(10 % of 3.4)		\$27,254
3.4 Construction cost			
3.4.1 Building structure costs			\$89,607
3.4.2 Equipment costs			\$121,662
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)		\$61,268
Subtotal of 3.4			\$272,537
3.5 Construction management	(17 % of 3.4)		\$46,604
3.6 Management reserve	(10 % of 3.4)		\$27,254
3.7 Contingency	(25 % of 3.1 through 3.5)		\$108,402
Subtotal 3.0			\$569,262
4.0 Operations budget funded activities (see Sect. 7)			
4.1 Conceptual design	(1.5 % of 3.0)		\$8,539
4.2 Safety assurance	(1 % of 3.0)		\$5,693
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)			\$6,000
4.4 Preparation for operations	(100 % of 5.0)		\$70,480
4.5 Project management	(10 % of 4.1 through 4.4)		\$9,071
Subtotal 4.0			\$99,783
Total initial cost (1.0, 2.0, 3.0 & 4.0)			\$772,310
5.0 Operating and maintenance costs			
5.1 Annual operating costs			\$37,520
5.2 Annual utility costs			\$886
5.3 Annual material costs			\$5,291
5.4 Annual maintenance costs			\$12,687
5.5 Contingency	(25 % of 5.1 through 5.4)		\$14,096
5.6 Subtotal 5.0			\$70,480
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)			\$1,409,600
6.0 Decontamination & decommissioning			\$54,467
7.0 ROM life cycle costs (20 years operation)			\$2,236,377
Storage O & M			
Total ROM Life cycle costs			

Table 4-1. Continued.

Cost component		Cost Items	Cost (\$ x 1000) System A-7 Slagging Rotary Kiln
1.0	Studies and bench scale test costs		
	1.1	Manpower costs during research	\$15,900
	1.2	Equipment costs	\$1,700
	1.3	Installation costs	\$1,000
	1.4	Project management before title I (10 % of 1.1 through 1.3)	\$1,860
	1.5	Contingency (25 % of 1.1 through 1.4)	\$5,115
		Subtotal 1.0	\$25,575
2.0	Demonstration costs		
	2.1	Manpower costs during demonstration	\$10,800
	2.2	Design cost (30 % of 2.5)	\$8,321
	2.3	Inspection cost (7 % of 2.5)	\$1,941
	2.4	Project management (10 % of 2.5)	\$2,774
	2.5	Construction cost	
		2.5.1 Building structure costs	\$3,500
		2.5.2 Equipment costs	\$18,000
		2.5.3 Indirect (29 % of 2.5.1 & 2.5.2)	\$6,235
		Subtotal of 2.5	\$27,735
	2.6	Construction management costs (17 % of 2.5)	\$4,743
	2.7	Management Reserve (10 % of 2.5)	\$2,774
	2.8	Contingency (25 % of 2.1 through 2.7)	\$14,772
		Subtotal 2.0	\$73,858
3.0	Production facility construction costs		
	3.1	Design cost (25 % of 3.4)	\$56,769
	3.2	Inspection cost (7 % of 3.4)	\$15,895
	3.3	Project management (10 % of 3.4)	\$22,707
	3.4	Construction cost	
		3.4.1 Building structure costs	\$77,689
		3.4.2 Equipment costs	\$98,338
		3.4.3 Indirect (29 % of 3.4.1 & 3.4.2)	\$51,048
		Subtotal of 3.4	\$227,075
	3.5	Construction management (17 % of 3.4)	\$38,830
	3.6	Management Reserve (10 % of 3.4)	\$22,707
	3.7	Contingency (25 % of 3.1 through 3.5)	\$90,319
		Subtotal 3.0	\$474,302
4.0	Operations Budget Funded Activities (See Sect. 7)		
	4.1	Conceptual design (1.5 % of 3.0)	\$7,115
	4.2	Safety assurance (1 % of 3.0)	\$4,743
	4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)	\$6,000
	4.4	Preparation for operations (100 % of 5.0)	\$60,903
	4.5	Project Management (10 % of 4.1 through 4.4)	\$7,876
		Subtotal 4.0	\$86,636
		Total Initial Cost (1.0,2.0,3.0 & 4.0)	\$660,372
5.0	Operating and maintenance costs		
	5.1	Annual operating costs	\$34,020
	5.2	Annual utility costs	\$691
	5.3	Annual material costs	\$3,090
	5.4	Annual maintenance costs	\$10,921
	5.5	Contingency (25 % of 5.1 through 5.4)	\$12,181
	5.6	Subtotal 5.0	\$60,903
	5.7	Total 20,000 year O & M cost (20,000 times Subtotal 5.0)	\$1,218,058
6.0	Decontamination & Decommissioning		
			\$49,256
7.0	ROM Life cycle costs (20,000 years operation)		
			\$1,927,685

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System B-1 Pyrolyzer, oxygen
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$18,900
1.2 Equipment costs		\$2,200
1.3 Installation costs		\$1,100
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,220
1.5 Contingency	(25 % of 1.1 through 1.4)	\$6,105
Subtotal 1.0		\$30,525
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$10,062
2.3 Inspection cost	(7 % of 2.5)	\$2,348
2.4 Project management	(10 % of 2.5)	\$3,354
2.5 Construction cost		
2.5.1 Building structure costs		\$4,000
2.5.2 Equipment costs		\$22,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$7,540
Subtotal of 2.5		\$33,540
2.6 Construction management costs	(17 % of 2.5)	\$5,735
2.7 Management reserve	(10 % of 2.5)	\$3,354
2.8 Contingency	(25 % of 2.1 through 2.7)	\$17,298
Subtotal 2.0		\$86,491
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$63,167
3.2 Inspection cost	(7 % of 3.4)	\$17,687
3.3 Project management	(10 % of 3.4)	\$25,267
3.4 Construction cost		
3.4.1 Building structure costs		\$85,055
3.4.2 Equipment costs		\$110,812
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$56,801
Subtotal of 3.4		\$252,668
3.5 Construction management	(17 % of 3.4)	\$43,206
3.6 Management reserve	(10 % of 3.4)	\$25,267
3.7 Contingency	(25 % of 3.1 through 3.5)	\$100,499
Subtotal 3.0		\$527,761
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$7,916
4.2 Safety assurance	(1 % of 3.0)	\$5,278
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$72,190
4.5 Project management	(10 % of 4.1 through 4.4)	\$9,138
Subtotal 4.0		\$100,522
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$745,300
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$39,200
5.2 Annual utility costs		\$857
5.3 Annual material costs		\$6,233
5.4 Annual maintenance costs		\$11,462
5.5 Contingency	(25 % of 5.1 through 5.4)	\$14,438
5.6 Subtotal 5.0		\$72,190
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,443,800
6.0 Decontamination & decommissioning		\$53,144
7.0 ROM life cycle costs (20 years operation)		\$2,242,244
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System C-1 Plasma arc furnace
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$18,000
1.2 Equipment costs		\$2,200
1.3 Installation costs		\$1,100
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,130
1.5 Contingency	(25 % of 1.1 through 1.4)	\$5,858
Subtotal 1.0		\$29,288
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$7,740
2.3 Inspection cost	(7 % of 2.5)	\$1,806
2.4 Project management	(10 % of 2.5)	\$2,580
2.5 Construction cost		
2.5.1 Building structure costs		\$3,000
2.5.2 Equipment costs		\$17,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$5,800
Subtotal of 2.5		\$25,800
2.6 Construction management costs	(17 % of 2.5)	\$4,412
2.7 Management reserve	(10 % of 2.5)	\$2,580
2.8 Contingency	(25 % of 2.1 through 2.7)	\$13,929
Subtotal 2.0		\$69,647
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$54,894
3.2 Inspection cost	(7 % of 3.4)	\$15,370
3.3 Project management	(10 % of 3.4)	\$21,958
3.4 Construction cost		
3.4.1 Building structure costs		\$79,647
3.4.2 Equipment costs		\$90,568
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$49,362
Subtotal of 3.4		\$219,576
3.5 Construction management	(17 % of 3.4)	\$37,548
3.6 Management reserve	(10 % of 3.4)	\$21,958
3.7 Contingency	(25 % of 3.1 through 3.5)	\$87,336
Subtotal 3.0		\$458,640
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$6,880
4.2 Safety assurance	(1 % of 3.0)	\$4,586
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$64,167
4.5 Project management	(10 % of 4.1 through 4.4)	\$8,163
Subtotal 4.0		\$89,796
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$647,371
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$35,700
5.2 Annual utility costs		\$1,154
5.3 Annual material costs		\$5,187
5.4 Annual maintenance costs		\$9,292
5.5 Contingency	(25 % of 5.1 through 5.4)	\$12,833
5.6 Subtotal 5.0		\$64,167
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,283,333
6.0 Decontamination & decommissioning		\$50,053
7.0 ROM life cycle costs (20 years operation)		\$1,980,756
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (\$ x 1000)	
		System C-2	Plasma Furnace, CO ₂ Retention
1.0	Studies and bench scale test costs		
1.1	Manpower costs during research		\$16,950
1.2	Equipment costs		\$2,200
1.3	Installation costs		\$1,100
1.4	Project management before title I (10 % of 1.1 through 1.3)		\$2,025
1.5	Contingency (25 % of 1.1 through 1.4)		\$5,569
	Subtotal 1.0		\$27,844
2.0	Demonstration costs		
2.1	Manpower costs during demonstration		\$10,800
2.2	Design cost (30 % of 2.5)		\$8,321
2.3	Inspection cost (7 % of 2.5)		\$1,941
2.4	Project management (10 % of 2.5)		\$2,774
2.5	Construction cost		
2.5.1	Building structure costs		\$3,500
2.5.2	Equipment costs		\$18,000
2.5.3	Indirect (29 % of 2.5.1 & 2.5.2)		\$6,235
	Subtotal of 2.5		\$27,735
2.6	Construction management costs (17 % of 2.5)		\$4,743
2.7	Management Reserve (10 % of 2.5)		\$2,774
2.8	Contingency (25 % of 2.1 through 2.7)		\$14,772
	Subtotal 2.0		\$73,858
3.0	Production facility construction costs		
3.1	Design cost (25 % of 3.4)		\$61,693
3.2	Inspection cost (7 % of 3.4)		\$17,274
3.3	Project management (10 % of 3.4)		\$24,677
3.4	Construction cost		
3.4.1	Building structure costs		\$82,992
3.4.2	Equipment costs		\$108,305
3.4.3	Indirect (29 % of 3.4.1 & 3.4.2)		\$55,476
	Subtotal of 3.4		\$246,773
3.5	Construction management (17 % of 3.4)		\$42,198
3.6	Management Reserve (10 % of 3.4)		\$24,677
3.7	Contingency (25 % of 3.1 through 3.5)		\$98,154
	Subtotal 3.0		\$515,447
4.0	Operations Budget Funded Activities (See Sect. 7)		
4.1	Conceptual design (1.5 % of 3.0)		\$7,732
4.2	Safety assurance (1 % of 3.0)		\$5,154
4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)		\$6,000
4.4	Preparation for operations (100 % of 5.0)		\$66,698
4.5	Project Management (10 % of 4.1 through 4.4)		\$8,558
	Subtotal 4.0		\$94,143
	Total Initial Cost (1.0,2.0,3.0 & 4.0)		\$711,291
5.0	Operating and maintenance costs		
5.1	Annual operating costs		\$35,140
5.2	Annual utility costs		\$672
5.3	Annual material costs		\$5,997
5.4	Annual maintenance costs		\$11,550
5.5	Contingency (25 % of 5.1 through 5.4)		\$13,340
5.6	Subtotal 5.0		\$66,698
5.7	Total 20.000 year O & M cost (20.000 times Subtotal 5.0)		\$1,333,965
6.0	Decontamination & Decommissioning		\$50,526
7.0	ROM Life cycle costs (20.000 years operation)		\$2,095,782

Table 4-1. Continued.

Cost component	Cost Items	Cost (\$ x 1000)	
		System C-3 Plasma Gasification	
1.0	Studies and bench scale test costs		
1.1	Manpower costs during research		\$16,500
1.2	Equipment costs		\$2,400
1.3	Installation costs		\$1,200
1.4	Project management before title I (10 % of 1.1 through 1.3)		\$2,010
1.5	Contingency (25 % of 1.1 through 1.4)		\$5,528
	Subtotal 1.0		\$27,638
2.0	Demonstration costs		
2.1	Manpower costs during demonstration		\$7,800
2.2	Design cost (30 % of 2.5)		\$6,463
2.3	Inspection cost (7 % of 2.5)		\$1,508
2.4	Project management (10 % of 2.5)		\$2,154
2.5	Construction cost		
2.5.1	Building structure costs		\$2,700
2.5.2	Equipment costs		\$14,000
2.5.3	Indirect (29 % of 2.5.1 & 2.5.2)		\$4,843
	Subtotal of 2.5		\$21,543
2.6	Construction management costs (17 % of 2.5)		\$3,684
2.7	Management Reserve (10 % of 2.5)		\$2,154
2.8	Contingency (25 % of 2.1 through 2.7)		\$11,327
	Subtotal 2.0		\$56,633
3.0	Production facility construction costs		
3.1	Design cost (25 % of 3.4)		\$59,656
3.2	Inspection cost (7 % of 3.4)		\$16,704
3.3	Project management (10 % of 3.4)		\$23,862
3.4	Construction cost		
3.4.1	Building structure costs		\$77,700
3.4.2	Equipment costs		\$107,281
3.4.3	Indirect (29 % of 3.4.1 & 3.4.2)		\$53,644
	Subtotal of 3.4		\$238,625
3.5	Construction management (17 % of 3.4)		\$40,805
3.6	Management Reserve (10 % of 3.4)		\$23,862
3.7	Contingency (25 % of 3.1 through 3.5)		\$94,913
	Subtotal 3.0		\$498,427
4.0	Operations Budget Funded Activities (See Sect. 7)		
4.1	Conceptual design (1.5 % of 3.0)		\$7,476
4.2	Safety assurance (1 % of 3.0)		\$4,984
4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)		\$6,000
4.4	Preparation for operations (100 % of 5.0)		\$60,527
4.5	Project Management (10 % of 4.1 through 4.4)		\$7,899
	Subtotal 4.0		\$86,886
	Total Initial Cost (1.0,2.0,3.0 & 4.0)		\$669,584
5.0	Operating and maintenance costs		
5.1	Annual operating costs		\$34,020
5.2	Annual utility costs		\$633
5.3	Annual material costs		\$2,777
5.4	Annual maintenance costs		\$10,991
5.5	Contingency (25 % of 5.1 through 5.4)		\$12,105
5.6	Subtotal 5.0		\$60,527
5.7	Total 20,000 year O & M cost (20,000 times Subtotal 5.0)		\$1,210,535
6.0	Decontamination & Decommissioning		\$48,991
7.0	ROM Life cycle costs (20,000 years operation)		\$1,929,110

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000)	
		System D-1 Fixed hearth, oxygen, CO, retention	
1.0	Studies and bench-scale test costs		
	1.1 Manpower costs during research		\$19,800
	1.2 Equipment costs		\$2,400
	1.3 Installation costs		\$1,600
	1.4 Project management before title 1 (10 % of 1.1 through 1.3)		\$2,380
	1.5 Contingency (25 % of 1.1 through 1.4)		\$6,545
	Subtotal 1.0		\$32,725
2.0	Demonstration costs		
	2.1 Manpower costs during demonstration		\$10,800
	2.2 Design cost (30 % of 2.5)		\$6,966
	2.3 Inspection cost (7 % of 2.5)		\$1,625
	2.4 Project management (10 % of 2.5)		\$2,322
	2.5 Construction cost		
	2.5.1 Building structure costs		\$3,000
	2.5.2 Equipment costs		\$15,000
	2.5.3 Indirect (29 % of 2.5.1 & 2.5.2)		\$5,220
	Subtotal of 2.5		\$23,220
	2.6 Construction management costs (17 % of 2.5)		\$3,971
	2.7 Management reserve (10 % of 2.5)		\$2,322
	2.8 Contingency (25 % of 2.1 through 2.7)		\$12,807
	Subtotal 2.0		\$64,033
3.0	Production facility construction costs		
	3.1 Design cost (25 % of 3.4)		\$66,901
	3.2 Inspection cost (7 % of 3.4)		\$18,732
	3.3 Project management (10 % of 3.4)		\$26,761
	3.4 Construction cost		
	3.4.1 Building structure costs		\$85,055
	3.4.2 Equipment costs		\$122,391
	3.4.3 Indirect (29 % of 3.4.1 & 3.4.2)		\$60,159
	Subtotal of 3.4		\$267,605
	3.5 Construction management (17 % of 3.4)		\$45,761
	3.6 Management reserve (10 % of 3.4)		\$26,761
	3.7 Contingency (25 % of 3.1 through 3.5)		\$106,440
	Subtotal 3.0		\$558,961
4.0	Operations budget funded activities (see Sect. 7)		
	4.1 Conceptual design (1.5 % of 3.0)		\$8,384
	4.2 Safety assurance (1 % of 3.0)		\$5,590
	4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
	4.4 Preparation for operations (100 % of 5.0)		\$76,184
	4.5 Project management (10 % of 4.1 through 4.4)		\$9,616
	Subtotal 4.0		\$105,774
	Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$761,492
5.0	Operating and maintenance costs		
	5.1 Annual operating costs		\$39,760
	5.2 Annual utility costs		\$1,417
	5.3 Annual material costs		\$7,123
	5.4 Annual maintenance costs		\$12,647
	5.5 Contingency (25 % of 5.1 through 5.4)		\$15,237
	5.6 Subtotal 5.0		\$76,184
	5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,523,678
6.0	Decontamination & decommissioning		\$53,144
7.0	ROM life cycle costs (20 years operation)		\$2,338,314
	Storage O & M		
	Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component	Cost Items	Cost (x 1000) System E-1 Rotary kiln, air, thermal desorber
1.0 Studies and bench-scale test costs		
1.1 Manpower costs during research		\$19,800
1.2 Equipment costs		\$2,200
1.3 Installation costs		\$1,100
1.4 Project management before title 1	(10 % of 1.1 through 1.3)	\$2,310
1.5 Contingency	(25 % of 1.1 through 1.4)	\$6,353
Subtotal 1.0		\$31,763
2.0 Demonstration costs		
2.1 Manpower costs during demonstration		\$10,800
2.2 Design cost	(30 % of 2.5)	\$6,889
2.3 Inspection cost	(7 % of 2.5)	\$1,607
2.4 Project management	(10 % of 2.5)	\$2,296
2.5 Construction cost		
2.5.1 Building structure costs		\$2,800
2.5.2 Equipment costs		\$15,000
2.5.3 Indirect	(29 % of 2.5.1 & 2.5.2)	\$5,162
Subtotal of 2.5		\$22,962
2.6 Construction management costs	(17 % of 2.5)	\$3,927
2.7 Management reserve	(10 % of 2.5)	\$2,296
2.8 Contingency	(25 % of 2.1 through 2.7)	\$12,694
Subtotal 2.0		\$63,471
3.0 Production facility construction costs		
3.1 Design cost	(25 % of 3.4)	\$63,618
3.2 Inspection cost	(7 % of 3.4)	\$17,813
3.3 Project management	(10 % of 3.4)	\$25,447
3.4 Construction cost		
3.4.1 Building structure costs		\$85,775
3.4.2 Equipment costs		\$111,490
3.4.3 Indirect	(29 % of 3.4.1 & 3.4.2)	\$57,207
Subtotal of 3.4		\$254,472
3.5 Construction management	(17 % of 3.4)	\$43,515
3.6 Management reserve	(10 % of 3.4)	\$25,447
3.7 Contingency	(25 % of 3.1 through 3.5)	\$101,216
Subtotal 3.0		\$531,528
4.0 Operations budget funded activities (see Sect. 7)		
4.1 Conceptual design	(1.5 % of 3.0)	\$7,973
4.2 Safety assurance	(1 % of 3.0)	\$5,315
4.3 NEPA permitting (\$ 6 million for EIS, \$1 million for EA)		\$6,000
4.4 Preparation for operations	(100 % of 5.0)	\$70,609
4.5 Project management	(10 % of 4.1 through 4.4)	\$8,990
Subtotal 4.0		\$98,887
Total initial cost (1.0, 2.0, 3.0 & 4.0)		\$725,648
5.0 Operating and maintenance costs		
5.1 Annual operating costs		\$38,080
5.2 Annual utility costs		\$1,134
5.3 Annual material costs		\$5,601
5.4 Annual maintenance costs		\$11,672
5.5 Contingency	(25 % of 5.1 through 5.4)	\$14,122
5.6 Subtotal 5.0		\$70,609
5.7 Total 20 year O & M cost (20 times Subtotal 5.0)		\$1,412,175
6.0 Decontamination & decommissioning		\$53,380
7.0 ROM life cycle costs (20 years operation)		\$2,191,203
Storage O & M		
Total ROM Life cycle costs		

Table 4-1. Continued.

Cost component		Cost Items	Cost (\$ x 1000) System F-1 Molten Salt Oxidation
1.0	Studies and bench scale test costs		
	1.1	Manpower costs during research	\$20,100
	1.2	Equipment costs	\$2,200
	1.3	Installation costs	\$1,100
	1.4	Project management before title I (10 % of 1.1 through 1.3)	\$2,340
	1.5	Contingency (25 % of 1.1 through 1.4)	\$6,435
		Subtotal 1.0	\$32,175
2.0	Demonstration costs		
	2.1	Manpower costs during demonstration	\$7,050
	2.2	Design cost (30 % of 2.5)	\$4,528
	2.3	Inspection cost (7 % of 2.5)	\$1,057
	2.4	Project management (10 % of 2.5)	\$1,509
	2.5	Construction cost	
		2.5.1 Building structure costs	\$2,200
		2.5.2 Equipment costs	\$9,500
		2.5.3 Indirect (29 % of 2.5.1 & 2.5.2)	\$3,393
		Subtotal of 2.5	\$15,093
	2.6	Construction management costs (17 % of 2.5)	\$2,581
	2.7	Management Reserve (10 % of 2.5)	\$1,509
	2.8	Contingency (25 % of 2.1 through 2.7)	\$8,332
		Subtotal 2.0	\$41,659
3.0	Production facility construction costs		
	3.1	Design cost (25 % of 3.4)	\$69,004
	3.2	Inspection cost (7 % of 3.4)	\$19,321
	3.3	Project management (10 % of 3.4)	\$27,602
	3.4	Construction cost	
		3.4.1 Building structure costs	\$90,321
		3.4.2 Equipment costs	\$123,644
		3.4.3 Indirect (29 % of 3.4.1 & 3.4.2)	\$62,050
		Subtotal of 3.4	\$276,015
	3.5	Construction management (17 % of 3.4)	\$47,199
	3.6	Management Reserve (10 % of 3.4)	\$27,602
	3.7	Contingency (25 % of 3.1 through 3.5)	\$109,785
		Subtotal 3.0	\$576,527
4.0	Operations Budget Funded Activities (See Sect. 7)		
	4.1	Conceptual design (1.5 % of 3.0)	\$8,648
	4.2	Safety assurance (1 % of 3.0)	\$5,765
	4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)	\$6,000
	4.4	Preparation for operations (100 % of 5.0)	\$73,363
	4.5	Project Management (10 % of 4.1 through 4.4)	\$9,378
		Subtotal 4.0	\$103,153
		Total Initial Cost (1.0,2.0,3.0 & 4.0)	\$753,514
5.0	Operating and maintenance costs		
	5.1	Annual operating costs	\$39,760
	5.2	Annual utility costs	\$826
	5.3	Annual material costs	\$5,067
	5.4	Annual maintenance costs	\$13,037
	5.5	Contingency (25 % of 5.1 through 5.4)	\$14,673
	5.6	Subtotal 5.0	\$73,363
	5.7	Total 20.000 year O & M cost (20.000 times Subtotal 5.0)	\$1,467,250
6.0	Decontamination & Decommissioning		
			\$54,445
7.0	ROM Life cycle costs (20.000 years operation)		
			\$2,275,209

Table 4-1. Continued.

Cost component		Cost Items	Cost (\$ x 1000) System G-1 Molten Metal Waste Destruction
1.0	Studies and bench scale test costs		
	1.1	Manpower costs during research	\$15,750
	1.2	Equipment costs	\$1,700
	1.3	Installation costs	\$1,000
	1.4	Project management before title I (10 % of 1.1 through 1.3)	\$1,845
	1.5	Contingency (25 % of 1.1 through 1.4)	\$5,074
		Subtotal 1.0	\$25,369
2.0	Demonstration costs		
	2.1	Manpower costs during demonstration	\$7,800
	2.2	Design cost (30 % of 2.5)	\$7,237
	2.3	Inspection cost (7 % of 2.5)	\$1,689
	2.4	Project management (10 % of 2.5)	\$2,412
	2.5	Construction cost	
	2.5.1	Building structure costs	\$2,700
	2.5.2	Equipment costs	\$16,000
	2.5.3	Indirect (29 % of 2.5.1 & 2.5.2)	\$5,423
		Subtotal of 2.5	\$24,123
	2.6	Construction management costs (17 % of 2.5)	\$4,125
	2.7	Management Reserve (10 % of 2.5)	\$2,412
	2.8	Contingency (25 % of 2.1 through 2.7)	\$12,450
		Subtotal 2.0	\$62,248
3.0	Production facility construction costs		
	3.1	Design cost (25 % of 3.4)	\$53,795
	3.2	Inspection cost (7 % of 3.4)	\$15,063
	3.3	Project management (10 % of 3.4)	\$21,518
	3.4	Construction cost	
	3.4.1	Building structure costs	\$85,379
	3.4.2	Equipment costs	\$81,427
	3.4.3	Indirect (29 % of 3.4.1 & 3.4.2)	\$48,374
		Subtotal of 3.4	\$215,180
	3.5	Construction management (17 % of 3.4)	\$36,796
	3.6	Management Reserve (10 % of 3.4)	\$21,518
	3.7	Contingency (25 % of 3.1 through 3.5)	\$85,588
		Subtotal 3.0	\$449,457
4.0	Operations Budget Funded Activities (See Sect. 7)		
	4.1	Conceptual design (1.5 % of 3.0)	\$6,742
	4.2	Safety assurance (1 % of 3.0)	\$4,495
	4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)	\$6,000
	4.4	Preparation for operations (100 % of 5.0)	\$61,004
	4.5	Project Management (10 % of 4.1 through 4.4)	\$7,824
		Subtotal 4.0	\$86,064
	Total Initial Cost (1.0,2.0,3.0 & 4.0)		\$623,138
5.0	Operating and maintenance costs		
	5.1	Annual operating costs	\$33,320
	5.2	Annual utility costs	\$673
	5.3	Annual material costs	\$6,364
	5.4	Annual maintenance costs	\$8,446
	5.5	Contingency (25 % of 5.1 through 5.4)	\$12,201
	5.6	Subtotal 5.0	\$61,004
	5.7	Total 20,000 year O & M cost (20,000 times Subtotal 5.0)	\$1,220,078
6.0	Decontamination & Decommissioning		\$50,266
7.0	ROM Life cycle costs (20,000 years operation)		\$1,893,481

Table 4-1. Continued.

Cost component		Cost Items	Cost (\$ x 1000) System H-1 Steam Gasification
1.0	Studies and bench scale test costs		
	1.1	Manpower costs during research	\$20,100
	1.2	Equipment costs	\$2,700
	1.3	Installation costs	\$1,300
	1.4	Project management before title I (10 % of 1.1 through 1.3)	\$2,410
	1.5	Contingency (25 % of 1.1 through 1.4)	\$6,628
		Subtotal 1.0	\$33,138
2.0	Demonstration costs		
	2.1	Manpower costs during demonstration	\$5,250
	2.2	Design cost (30 % of 2.5)	\$3,135
	2.3	Inspection cost (7 % of 2.5)	\$731
	2.4	Project management (10 % of 2.5)	\$1,045
	2.5	Construction cost	
		2.5.1 Building structure costs	\$1,600
		2.5.2 Equipment costs	\$6,500
		2.5.3 Indirect (29 % of 2.5.1 & 2.5.2)	\$2,349
		Subtotal of 2.5	\$10,449
	2.6	Construction management costs (17 % of 2.5)	\$1,787
	2.7	Management Reserve (10 % of 2.5)	\$1,045
	2.8	Contingency (25 % of 2.1 through 2.7)	\$5,860
		Subtotal 2.0	\$29,302
3.0	Production facility construction costs		
	3.1	Design cost (25 % of 3.4)	\$70,328
	3.2	Inspection cost (7 % of 3.4)	\$19,692
	3.3	Project management (10 % of 3.4)	\$28,131
	3.4	Construction cost	
		3.4.1 Building structure costs	\$87,821
		3.4.2 Equipment costs	\$130,249
		3.4.3 Indirect (29 % of 3.4.1 & 3.4.2)	\$63,240
		Subtotal of 3.4	\$281,310
	3.5	Construction management (17 % of 3.4)	\$48,104
	3.6	Management Reserve (10 % of 3.4)	\$28,131
	3.7	Contingency (25 % of 3.1 through 3.5)	\$111,891
		Subtotal 3.0	\$587,587
4.0	Operations Budget Funded Activities (See Sect. 7)		
	4.1	Conceptual design (1.5 % of 3.0)	\$8,814
	4.2	Safety assurance (1 % of 3.0)	\$5,876
	4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)	\$6,000
	4.4	Preparation for operations (100 % of 5.0)	\$72,308
	4.5	Project Management (10 % of 4.1 through 4.4)	\$9,300
		Subtotal 4.0	\$102,297
		Total Initial Cost (1.0,2.0,3.0 & 4.0)	\$752,324
5.0	Operating and maintenance costs		
	5.1	Annual operating costs	\$39,760
	5.2	Annual utility costs	\$686
	5.3	Annual material costs	\$4,935
	5.4	Annual maintenance costs	\$12,466
	5.5	Contingency (25 % of 5.1 through 5.4)	\$14,462
	5.6	Subtotal 5.0	\$72,308
	5.7	Total 20.000 year O & M cost (20.000 times Subtotal 5.0)	\$1,446,160
6.0	Decontamination & Decommissioning		
			\$53,756
7.0	ROM Life cycle costs (20.000 years operation)		
			\$2,252,240

Table 4-1. Continued.

Cost	component	Cost Items	Cost (\$ x 1000) System J-1 Joule Heated Vitrification
1.0	Studies and bench scale test costs		
	1.1 Manpower costs during research		\$17,100
	1.2 Equipment costs		\$2,200
	1.3 Installation costs		\$1,100
	1.4 Project management before title I (10 % of 1.1 through 1.3)		\$2,040
	1.5 Contingency (25 % of 1.1 through 1.4)		\$5,610
	Subtotal 1.0		\$28,050
2.0	Demonstration costs		
	2.1 Manpower costs during demonstration		\$7,650
	2.2 Design cost (30 % of 2.5)		\$5,186
	2.3 Inspection cost (7 % of 2.5)		\$1,210
	2.4 Project management (10 % of 2.5)		\$1,729
	2.5 Construction cost		
	2.5.1 Building structure costs		\$2,400
	2.5.2 Equipment costs		\$11,000
	2.5.3 Indirect (29 % of 2.5.1 & 2.5.2)		\$3,886
	Subtotal of 2.5		\$17,286
	2.6 Construction management costs (17 % of 2.5)		\$2,956
	2.7 Management Reserve (10 % of 2.5)		\$1,729
	2.8 Contingency (25 % of 2.1 through 2.7)		\$9,436
	Subtotal 2.0		\$47,181
3.0	Production facility construction costs		
	3.1 Design cost (25 % of 3.4)		\$56,809
	3.2 Inspection cost (7 % of 3.4)		\$15,906
	3.3 Project management (10 % of 3.4)		\$22,723
	3.4 Construction cost		
	3.4.1 Building structure costs		\$81,451
	3.4.2 Equipment costs		\$94,700
	3.4.3 Indirect (29 % of 3.4.1 & 3.4.2)		\$51,084
	Subtotal of 3.4		\$227,235
	3.5 Construction management (17 % of 3.4)		\$38,857
	3.6 Management Reserve (10 % of 3.4)		\$22,723
	3.7 Contingency (25 % of 3.1 through 3.5)		\$90,383
	Subtotal 3.0		\$474,636
4.0	Operations Budget Funded Activities (See Sect. 7)		
	4.1 Conceptual design (1.5 % of 3.0)		\$7,120
	4.2 Safety assurance (1 % of 3.0)		\$4,746
	4.3 NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)		\$6,000
	4.4 Preparation for operations (100 % of 5.0)		\$61,696
	4.5 Project Management (10 % of 4.1 through 4.4)		\$7,956
	Subtotal 4.0		\$87,518
	Total Initial Cost (1.0,2.0,3.0 & 4.0)		\$637,385
5.0	Operating and maintenance costs		
	5.1 Annual operating costs		\$36,540
	5.2 Annual utility costs		\$671
	5.3 Annual material costs		\$2,353
	5.4 Annual maintenance costs		\$9,793
	5.5 Contingency (25 % of 5.1 through 5.4)		\$12,339
	5.6 Subtotal 5.0		\$61,696
	5.7 Total 20,000 year O & M cost (20,000 times Subtotal 5.0)		\$1,233,913
6.0	Decontamination & Decommissioning		\$50,292
7.0	ROM Life cycle costs (20,000 years operation)		\$1,921,590

Table 4-1. Continued.

Cost component		Cost Items	Cost (\$ x 1000) System L-1 Thermal Desorption and
1.0	Studies and bench scale test costs		
	1.1	Manpower costs during research	\$19,050
	1.2	Equipment costs	\$2,200
	1.3	Installation costs	\$1,150
	1.4	Project management before title I (10 % of 1.1 through 1.3)	\$2,240
	1.5	Contingency (25 % of 1.1 through 1.4)	\$6,160
		Subtotal 1.0	\$30,800
2.0	Demonstration costs		
	2.1	Manpower costs during demonstration	\$4,650
	2.2	Design cost (30 % of 2.5)	\$2,786
	2.3	Inspection cost (7 % of 2.5)	\$650
	2.4	Project management (10 % of 2.5)	\$929
	2.5	Construction cost	
		2.5.1 Building structure costs	\$1,200
		2.5.2 Equipment costs	\$6,000
		2.5.3 Indirect (29 % of 2.5.1 & 2.5.2)	\$2,088
		Subtotal of 2.5	\$9,288
	2.6	Construction management costs (17 % of 2.5)	\$1,588
	2.7	Management Reserve (10 % of 2.5)	\$929
	2.8	Contingency (25 % of 2.1 through 2.7)	\$5,205
		Subtotal 2.0	\$26,026
3.0	Production facility construction costs		
	3.1	Design cost (25 % of 3.4)	\$60,413
	3.2	Inspection cost (7 % of 3.4)	\$16,916
	3.3	Project management (10 % of 3.4)	\$24,165
	3.4	Construction cost	
		3.4.1 Building structure costs	\$80,632
		3.4.2 Equipment costs	\$106,695
		3.4.3 Indirect (29 % of 3.4.1 & 3.4.2)	\$54,325
		Subtotal of 3.4	\$241,651
	3.5	Construction management (17 % of 3.4)	\$41,322
	3.6	Management Reserve (10 % of 3.4)	\$24,165
	3.7	Contingency (25 % of 3.1 through 3.5)	\$96,117
		Subtotal 3.0	\$504,748
4.0	Operations Budget Funded Activities (See Sect. 7)		
	4.1	Conceptual design (1.5 % of 3.0)	\$7,571
	4.2	Safety assurance (1 % of 3.0)	\$5,047
	4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)	\$6,000
	4.4	Preparation for operations (100 % of 5.0)	\$71,429
	4.5	Project Management (10 % of 4.1 through 4.4)	\$9,005
		Subtotal 4.0	\$99,053
		Total Initial Cost (1.0,2.0,3.0 & 4.0)	\$660,627
5.0	Operating and maintenance costs		
	5.1	Annual operating costs	\$42,840
	5.2	Annual utility costs	\$763
	5.3	Annual material costs	\$2,870
	5.4	Annual maintenance costs	\$10,671
	5.5	Contingency (25 % of 5.1 through 5.4)	\$14,286
	5.6	Subtotal 5.0	\$71,429
	5.7	Total 20,000 year O & M cost (20,000 times Subtotal 5.0)	\$1,428,588
6.0	Decontamination & Decommissioning		
			\$54,287
7.0	ROM Life cycle costs (20,000 years operation)		
			\$2,143,501

Table 4-1. Continued.

Cost component	Cost Items	Cost (\$ x 1000)	
		System K-1 Thermal Desorption and	
1.0	Studies and bench scale test costs		
1.1	Manpower costs during research		\$19,050
1.2	Equipment costs		\$2,200
1.3	Installation costs		\$1,150
1.4	Project management before title I (10 % of 1.1 through 1.3)		\$2,240
1.5	Contingency (25 % of 1.1 through 1.4)		\$6,160
	Subtotal 1.0		\$30,800
2.0	Demonstration costs		
2.1	Manpower costs during demonstration		\$5,400
2.2	Design cost (30 % of 2.5)		\$3,251
2.3	Inspection cost (7 % of 2.5)		\$759
2.4	Project management (10 % of 2.5)		\$1,084
2.5	Construction cost		
2.5.1	Building structure costs		\$1,400
2.5.2	Equipment costs		\$7,000
2.5.3	Indirect (29 % of 2.5.1 & 2.5.2)		\$2,436
	Subtotal of 2.5		\$10,836
2.6	Construction management costs (17 % of 2.5)		\$1,853
2.7	Management Reserve (10 % of 2.5)		\$1,084
2.8	Contingency (25 % of 2.1 through 2.7)		\$6,066
	Subtotal 2.0		\$30,332
3.0	Production facility construction costs		
3.1	Design cost (25 % of 3.4)		\$58,256
3.2	Inspection cost (7 % of 3.4)		\$16,312
3.3	Project management (10 % of 3.4)		\$23,302
3.4	Construction cost		
3.4.1	Building structure costs		\$83,952
3.4.2	Equipment costs		\$96,688
3.4.3	Indirect (29 % of 3.4.1 & 3.4.2)		\$52,385
	Subtotal of 3.4		\$233,025
3.5	Construction management (17 % of 3.4)		\$39,847
3.6	Management Reserve (10 % of 3.4)		\$23,302
3.7	Contingency (25 % of 3.1 through 3.5)		\$92,686
	Subtotal 3.0		\$486,730
4.0	Operations Budget Funded Activities (See Sect. 7)		
4.1	Conceptual design (1.5 % of 3.0)		\$7,301
4.2	Safety assurance (1 % of 3.0)		\$4,867
4.3	NEPA permitting (\$ 6 Mill for EIS, \$1 Mill for EA)		\$6,000
4.4	Preparation for operations (100 % of 5.0)		\$69,935
4.5	Project Management (10 % of 4.1 through 4.4)		\$8,810
	Subtotal 4.0		\$96,914
	Total Initial Cost (1.0,2.0,3.0 & 4.0)		\$644,776
5.0	Operating and maintenance costs		
5.1	Annual operating costs		\$42,840
5.2	Annual utility costs		\$762
5.3	Annual material costs		\$2,809
5.4	Annual maintenance costs		\$9,537
5.5	Contingency (25 % of 5.1 through 5.4)		\$13,987
5.6	Subtotal 5.0		\$69,935
5.7	Total 20,000 year O & M cost (20,000 times Subtotal 5.0)		\$1,398,703
6.0	Decontamination & Decommissioning		\$54,657
7.0	ROM Life cycle costs (20,000 years operation)		\$2,098,135

Table 4-2. Estimated facility administration staff for the baseline system, rotary kiln using air (System A-1).

Job	FTE workers
Accountant	1
Secretary and clerk	2
Document control	2
Manager-dayshifts	2
Technical personnel	1
Communications	1
Environmental manager	1
Operations support and management	1
Quality control technicians	1
Security guard	4
Health physics technician	4
Testing laboratory	<u>7</u>
TOTAL	27

Table 4-3. Estimated facility operation staff for the baseline system, rotary kiln using air (System A-1).

Subsystem	Crews	Crew size	Number of 40-hour shifts	Total FTE workers
Receiving and preparation	7	4	4	112
Incineration	1	4	4	16
Air pollution control	1	1	4	4
Primary stabilization	1	4	4	16
Metal melting	1	4	1	4
Lead recovery	1	4	2	8
Metal decontamination	1	4	1	4
Aqueous waste treatment	1	4	4	16
Mercury amalgamation	1	4	1	4
Secondary stabilization	1	4	4	16
Special waste treatment	1	2	1	2
Support systems	1	1	4	<u>4</u>
TOTAL				206

Table 4-4. Total system life-cycle cost estimates (not including transportation) (in thousands of dollars).

System	Treatment cost* unit rate (\$/lb)	Normalized treatment* cost (system A-1 = 1.000)	Modified treatment cost** unit rate (\$/lb)	Normalized modified treatment** cost (system A-1 = 1.000)	Volumetric Flow rate (ft ³ /hr)	Total treatment cost (\$millions)	Final waste vol. (ft ³)	Disposal cost (\$millions)	Total life cycle cost (\$millions)
A-1 Rotary kiln, air	9.35	1.000	7.99	1.000	13.6	2,206.61	1,095,648	266.24	2,472.85
A-2 Rotary kiln, oxygen	9.34	0.999	7.98	0.999	13.6	2,204.99	1,095,648	266.24	2,471.24
A-3 Rotary kiln, air, wet APC	9.25	0.989	8.21	1.028	17.0	2,182.95	1,369,325	332.75	2,515.69
A-4 Rotary kiln, oxygen, CO2 retention	9.90	1.059	8.46	1.059	19.7	2,336.85	1,585,118	385.18	2,722.03
A-5 Rotary kiln, air, polymer stabilization	8.99	0.962	8.99	1.126	28.5	2,122.59	2,300,532	559.03	2,681.62
A-6 Rotary kiln, air, maximum recycling	9.64	1.031	8.25	1.032	10.7	2,275.66	864,018	209.96	2,485.62
A-7 Slagging rotary kiln	8.17	0.873	6.85	0.857	14.5	1,927.69	1,170,466	284.42	2,212.11
B-1 Indirectly heated pyrolyzer	10.10	1.080	8.63	1.081	13.6	2,384.52	1,095,648	266.24	2,650.76
C-1 Plasma furnace	8.59	0.918	7.37	0.923	13.2	2,026.86	1,066,540	259.17	2,286.03
C-2 Plasma furnace, CO2 retention	8.88	0.950	7.62	0.954	15.1	2,095.78	1,220,080	296.48	2,392.26
C-3 Plasma gasification	8.17	0.874	7.01	0.878	13.2	1,929.11	1,067,403	259.38	2,188.49
D-1 Fixed hearth pyrolyzer, CO2 retentio	10.78	1.153	10.59	1.325	15.2	2,545.31	1,226,221	297.97	2,843.28
E-1 Rotary kiln, air, thermal desorption	9.62	1.029	9.44	1.182	30.8	2,270.42	2,482,376	603.22	2,873.64
F-1 Molten salt oxidation	9.62	1.029	8.22	1.029	14.6	2,271.08	1,176,428	285.87	2,556.95
G-1 Molten metal waste destruction	8.02	0.858	6.80	0.852	11.5	1,893.48	929,131	225.78	2,119.26
H-1 Steam gasification	9.52	1.018	8.14	1.018	13.6	2,247.29	1,094,786	266.03	2,513.32
J-1 Joule-heated vitrification	8.14	0.871	6.96	0.871	13.6	1,921.59	1,095,217	266.14	2,187.73
K-1 Thermal desorption and MEO	8.28	0.886	8.28	1.037	42.6	1,955.02	3,435,031	834.71	2,789.74
L-1 Thermal desorption and SCWO	8.46	0.905	8.46	1.059	40.5	1,997.15	3,269,719	794.54	2,791.69

* The treatment cost unit rate is calculated by dividing the treatment cost by the total waste input to the ITTS facility for 20 years of operation. The treatment cost unit rate does not take into account the contaminated soil additive used for vitrification of waste.

** The modified treatment cost unit rate takes into account the contaminated soil used for vitrification in all systems except system K-1 and L-1. The soil additive mass flow rate ranges between 57 to 564 lb/hr.

Table 4-5. Life-cycle cost comparison for nineteen treatment processes (in thousands of dollars).

	Rotary kiln, air	Rotary kiln, oxygen	Rotary kiln, air, wet APC	Rotary kiln, oxygen, CO2 retention	Rotary kiln, air, polymer stabilization	Rotary kiln, air, maximum recycling	Slagging rotary kiln	Indirectly heated pyrolyzer	Plasma furnace	Plasma furnace with CO2 retention
ACTUAL COSTS										
System abbreviation	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2
TREATMENT (a)										
Items 1.0, 2.0, and 4.0	\$196,919	\$197,340	\$192,223	\$220,900	\$189,786	\$203,049	\$107,309	\$217,539	\$188,731	\$110,260
Item 3.0	\$554,377	\$535,818	\$542,387	\$557,524	\$490,866	\$569,262	\$474,302	\$527,761	\$458,640	\$515,447
Item 5.0	\$1,361,850	\$1,378,775	\$1,355,275	\$1,450,025	\$1,350,150	\$1,409,600	\$1,218,058	\$1,443,800	\$1,283,333	\$1,333,965
Item 6.0	\$54,171	\$53,776	\$53,776	\$53,776	\$52,497	\$54,467	\$49,256	\$53,144	\$50,053	\$50,526
Total Treatment PLCC	\$2,167,318	\$2,165,709	\$2,143,661	\$2,282,225	\$2,083,298	\$2,236,377	\$1,848,925	\$2,242,244	\$1,980,756	\$2,010,198
DISPOSAL										
Disposal PLCC	\$231,620	\$231,620	\$286,090	\$252,780	\$470,290	\$156,760	\$246,900	\$225,350	\$231,230	\$280,220
TOTAL TREATMENT & DISPOSAL										
PLCC	\$2,398,938	\$2,397,329	\$2,429,751	\$2,535,005	\$2,553,588	\$2,393,137	\$2,095,825	\$2,467,594	\$2,211,986	\$2,290,418

	Plasma gasification	Fixed-hearth pyrolyzer, oxygen, CO2 retention	Rotary kiln, air, thermal desorber	Molten salt oxidation	Molten Metal Waste Destruction	Steam gasification	Joule-heated vitrification	Thermal desorption and MEO	Thermal desorption and SCWO
ACTUAL COSTS									
System abbreviation	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
TREATMENT (a)									
Items 1.0, 2.0, and 4.0	\$92,169	\$202,531	\$194,120	\$83,211	\$95,440	\$71,459	\$83,187	\$69,942	\$65,830
Item 3.0	\$498,427	\$558,961	\$531,528	\$576,527	\$449,457	\$587,587	\$474,636	\$486,730	\$504,748
Item 5.0	\$1,210,535	\$1,523,678	\$1,412,175	\$1,467,250	\$1,220,078	\$1,390,160	\$1,233,913	\$1,398,703	\$1,428,588
Item 6.0	\$48,991	\$53,144	\$53,380	\$54,445	\$50,266	\$53,756	\$50,292	\$54,657	\$54,287
Total Treatment PLCC	\$1,850,123	\$2,338,314	\$2,191,203	\$2,181,433	\$1,815,241	\$2,102,962	\$1,842,028	\$2,010,032	\$2,053,453
DISPOSAL									
Disposal PLCC	\$219,470	\$260,620	\$723,070	\$223,390	\$223,390	\$205,750	\$217,510	\$758,350	\$756,390
TOTAL TREATMENT & DISPOSAL									
PLCC	\$2,069,593	\$2,598,934	\$2,914,273	\$2,404,823	\$2,038,631	\$2,308,712	\$2,059,538	\$2,768,382	\$2,809,843

(a) Work Breakdown Structure Elements used in developing Treatment PLCC are as follows:

- 1.0 Studies & Bench Scale Tests
- 2.0 Demonstration Costs
- 3.0 Production Facility Construction Costs
- 4.0 Operating Budget Funded Activities
- 5.0 Operating & Maintenance Costs
- 6.0 Decontamination & Decommissioning Costs

Table 4-6. Normalized treatment life-cycle cost comparison for the nineteen treatment processes (baseline cost in thousands of dollars).

	Rotary kiln, air (baseline system)	Rotary kiln, oxygen	Rotary kiln, air, wet APC	Rotary kiln, oxygen, CO2 retention	Rotary kiln, air, polymer stabilization	Rotary kiln, oxygen, maximum recycling	Slagging rotary kiln	Pyrolyzer, oxygen	Plasma furnace	Plasma furnace with CO2 retention
NORMALIZED COSTS										
System abbreviation	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2
TREATMENT (a)										
Items 1.0, 2.0, and 4.0	\$196,919	1.00	0.98	1.12	0.96	1.03	0.54	1.10	0.96	0.56
Item 3.0	\$554,377	0.97	0.98	1.01	0.89	1.03	0.86	0.95	0.83	0.93
Item 5.0	\$1,381,850	1.01	1.00	1.06	0.99	1.04	0.89	1.06	0.94	0.98
Item 6.0	\$54,171	0.99	0.99	0.99	0.97	1.01	0.91	0.98	0.92	0.93
Total Treatment PLCC	\$2,167,318	1.00	0.99	1.05	0.96	1.03	0.85	1.03	0.91	0.93
DISPOSAL										
Disposal PLCC	\$231,620	1.00	1.24	1.09	2.03	0.68	1.07	0.97	1.00	1.21
TOTAL TREATMENT & DISPOSAL PLCC	\$2,398,938	1.00	1.01	1.08	1.06	1.00	0.87	1.03	0.92	0.95

	Plasma gasification	Fixed-hearth pyrolyzer, oxygen, CO2 retention	Rotary kiln, air, thermal desorber	Molten salt oxidation	Molten Metal Waste Destruction	Steam gasification	Joule-heated vitrification	Thermal desorption and MEO	Thermal desorption and SCWO
NORMALIZED COSTS									
System abbreviation	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
TREATMENT (a)									
Items 1.0, 2.0, and 4.0	0.47	1.03	0.99	0.42	0.48	0.36	0.42	0.36	0.33
Item 3.0	0.90	1.01	0.96	1.04	0.81	1.06	0.86	0.88	0.91
Item 5.0	0.89	1.12	1.04	1.08	0.90	1.02	0.91	1.03	1.05
Item 6.0	0.90	0.98	0.99	1.01	0.93	0.99	0.93	1.01	1.00
Total Treatment PLCC	0.85	1.08	1.01	1.01	0.84	0.97	0.85	0.93	0.95
DISPOSAL									
Disposal PLCC	0.95	1.13	3.12	0.96	0.96	0.89	0.94	3.27	3.27
TOTAL TREATMENT & DISPOSAL PLCC	0.88	1.08	1.21	1.00	0.85	0.96	0.86	1.15	1.17

(a) Work Breakdown Structure Elements used in developing Treatment PLCC are as follows:

- 1.0 Studies & Bench Scale Tests
- 2.0 Demonstration Costs
- 3.0 Production Facility Construction Costs
- 4.0 Operating Budget Funded Activities
- 5.0 Operating & Maintenance Costs
- 6.0 Decontamination & Decommissioning Costs

Table 4-7. Treatment life-cycle cost estimate per subsystem (in thousands of dollars).

	Rotary kiln, air (baseline system)	Rotary kiln, oxygen	Rotary kiln, air, wet APC	Rotary kiln, oxygen, CO ₂ retention	Rotary kiln, air, polymer stabilization	Rotary kiln, oxygen, maximum recycling	Slagging rotary kiln	Pyrolyzer, oxygen	Plasma furnace	Plasma furnace with CO ₂ retention
ACTUAL COSTS										
System abbreviation	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2
Administration Building Subsystem	\$139,037	\$139,037	\$139,037	\$139,037	\$139,074	\$139,006	\$139,125	\$139,037	\$139,074	\$139,125
Receiving & Inspection Subsystem	\$666,796	\$666,796	\$666,796	\$666,796	\$666,832	\$666,765	\$660,054	\$783,333	\$660,054	\$660,054
Metal Decontamination Subsystem	\$61,878	\$61,878	\$61,878	\$61,878	\$61,914	\$61,846	\$61,963	\$61,878	\$61,914	\$61,963
Metal Melting Subsystem	\$92,110	\$92,110	\$92,110	\$92,110	\$92,146	\$92,079	(a)	\$92,110	(a)	(a)
Lead Recovery Subsystem	\$81,130	\$81,129	\$81,129	\$81,129	\$81,166	\$81,098	\$81,207	\$81,129	\$81,166	\$81,207
Primary Thermal Treatment Subsystem	\$161,490	\$199,288	\$161,490	\$198,876	\$161,526	\$193,018	\$245,835	\$171,211	\$201,833	\$318,510
Thermal Desorption Subsystem	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Air Pollution Control Subsystem	\$115,219	\$76,224	\$90,090	\$192,740	\$108,749	\$114,703	\$113,658	\$76,488	\$79,977	\$256,557
Aqueous Waste Treatment Subsystem	\$149,186	\$149,186	\$149,186	\$149,186	\$149,222	\$149,154	\$147,494	\$149,186	\$149,222	\$120,213
Primary Stabilization Subsystem	\$243,688	\$243,688	\$243,688	\$243,688	(a)	\$243,656	(a)	\$231,087	\$150,592	(a)
Secondary Stabilization Subsystem	\$80,942	\$81,148	\$82,414	\$80,942	\$246,681	\$55,715	\$79,560	\$80,942	\$80,978	\$72,204
Special Waste	\$29,350	\$29,351	\$29,351	\$29,351	\$29,387	\$29,319	\$29,429	\$29,351	\$29,387	\$29,429
Mercury Amalgamation Subsystem	\$52,244	\$51,625	\$52,244	\$52,244	\$52,280	\$52,212	\$52,302	\$52,244	\$52,280	\$52,302
Certify & Shipping Subsystem	\$193,049	\$193,049	\$193,049	\$193,049	\$193,085	\$193,017	\$207,046	\$193,049	\$193,085	\$193,173
Grout Stabilization Cost Package	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Salt Recovery Cost Package	(a)	(a)	(a)	(a)	(a)	\$63,620	(a)	(a)	(a)	(a)
Support Subsystem	\$101,200	\$101,200	\$101,200	\$101,200	\$101,236	\$101,169	\$110,012	\$101,200	\$101,236	\$111,044
Total Treatment PLCC	\$2,167,318	\$2,165,709	\$2,143,661	\$2,282,225	\$2,083,298	\$2,236,377	\$1,927,685	\$2,242,244	\$1,980,798	\$2,095,782

	Plasma gasification	Fixed-hearth pyrolyzer, oxygen, CO ₂ retention	Rotary kiln, air, thermal desorber	Molten salt oxidation	Molten Metal Waste Destruction	Steam gasification	Joule-heated vitrification	Thermal desorption and MEO	Thermal desorption and SCWO
ACTUAL COSTS									
System abbreviation	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
Administration Building Subsystem	\$139,125	\$139,037	\$138,978	\$139,047	\$139,175	\$139,047	\$139,083	\$139,047	\$139,047
Receiving & Inspection Subsystem	\$660,054	\$783,363	\$706,022	\$783,367	\$636,881	\$783,367	\$711,416	\$806,330	\$806,330
Metal Decontamination Subsystem	\$61,963	\$61,878	\$61,819	\$61,884	(a)	\$61,884	\$61,921	\$61,884	\$61,884
Metal Melting Subsystem	(a)	\$92,110	\$92,051	\$92,089	(a)	\$92,089	\$92,125	\$92,089	\$92,089
Lead Recovery Subsystem	\$81,207	\$81,129	\$81,070	\$81,129	\$81,257	\$81,129	\$81,165	\$81,129	\$81,129
Primary Thermal Treatment Subsystem	\$294,141	\$135,346	\$123,510	\$200,878	\$364,365	\$184,938	\$181,610	(a)	(a)
Thermal Desorption Subsystem	(a)	(a)	\$97,889	(a)	(a)	(a)	(a)	\$145,498	\$193,057
Air Pollution Control Subsystem	\$106,776	\$195,793	\$93,213	\$94,893	\$85,395	\$87,864	\$75,870	\$45,294	\$43,127
Aqueous Waste Treatment Subsystem	\$120,213	\$149,186	\$149,127	\$112,765	\$120,263	\$53,685	\$112,802	\$112,765	\$112,765
Primary Stabilization Subsystem	(a)	\$243,688	\$167,913	\$243,656	(a)	\$243,656	(a)	(a)	(a)
Secondary Stabilization Subsystem	\$80,977	\$80,942	\$80,883	\$80,898	\$81,027	\$80,898	\$80,935	\$78,393	\$78,366
Special Waste	\$29,429	\$29,351	\$29,292	\$29,351	\$29,479	\$29,351	\$29,387	\$29,351	\$29,351
Mercury Amalgamation Subsystem	\$52,038	\$52,244	\$52,185	\$52,224	\$52,352	\$52,224	\$52,179	\$52,224	\$52,224
Certify & Shipping Subsystem	\$193,173	\$193,049	\$208,142	\$193,094	\$193,223	\$193,094	\$193,127	\$324,395	\$324,395
Grout Stabilization Cost Package	(a)	(a)	\$7,968	(a)	(a)	(a)	(a)	\$19,803	\$19,803
Salt Recovery Cost Package	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Support Subsystem	\$110,013	\$101,200	\$101,141	\$109,934	\$110,063	\$109,934	\$109,970	\$109,934	\$109,934
Total Treatment PLCC	\$1,929,110	\$2,338,314	\$2,191,203	\$2,275,209	\$1,893,481	\$2,193,160	\$1,921,590	\$2,098,135	\$2,143,501

(a) Subsystems not included in this thermal treatment alternative.

Table 4-8. Cost Sensitivity to Post-Construction Preoperations (in millions of dollars)

Cost Risk Level	WBS 4.4	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
Level 0	100%	2,167	2,165	2,143	2,282	2,083	2,236	1,927	2,242	1,980	2,096	1,929	2,338	2,191	2,271	1,893	2,252	1,922	2,098	2,144
Level 1	100%	2,167	2,165	2,143		2,083	2,236	1,927						2,191						
Level 2	200%								2,321								2,332			
Level 3	300%				2,441					2,122			2,506					2,057		
Level 4	400%										2,316	2,129			2,517	2,095			2,329	2,379
PLCC Difference		None	None	None	\$159	None	None	None	\$79	\$142	\$220	\$200	\$168	None	\$246	\$202	\$80	\$135	\$231	\$235
Percent Increase		None	None	None	6.97%	None	None	None	3.52%	7.17%	10.50%	10.37%	7.19%	None	10.83%	10.67%	3.55%	7.02%	11.01%	10.96%

- Notes:
1. WBS 4.4 captures contingency for "Operations and Budget Funded Activities" and is related to annual operating cost (WBS 5.0).
 2. A WBS 4.4 contingency of 100% indicates one year of operations and maintenance costs are captured as the uncertainty costs for this "Operations and Budget Funded Activity" cost element.
 3. Cost risk levels are as follows:
 - Level 0 - Assumes that all systems have the same cost contingencies. Present ITTS PLCC costs have all the same contingencies.
 - Level 1 - Systems with the lowest cost risks. It is assumed that once the system is built it will be fully operational in one year with little cost risk.
 - Level 2 - Systems with the cost risks higher than level 1. It is assumed that once the system is built it will be fully operational in two years with moderate cost risk.
 - Level 3 - Systems with the cost risks higher than level 2. It is assumed that once the system is built it will be fully operational in 3 years with moderate to high cost risk.
 - Level 4 - Systems with the cost risks higher than level 3. It is assumed that once the system is built it will be fully operational in 4 years with high cost risk.
 4. Systems are ranked by level to indicate the cost risks associated with startup. The technologies that are not well established have a much higher probability of startup problems. The riskiest system will have the greatest probability of repetitive startup problems, redesign, and replacement of components or whole systems. Lower risk levels are associated with systems where component replacement with conventional technology will allow the system to function. For example, a system with the primary risk in the APC which could be wholly replaced will be assigned lower risk than a system with a risky main thermal treatment approach.

Figure 4-1. PLCC estimating steps.

Figure 4-2. Facility capital cost estimates for the subsystems of rotary kiln, air (System A-1).

Figure 4-3. Life-cycle cost estimates for subsystems of rotary kiln, air (System A-1).

Figure 4-4. Unit rate cost estimates for subsystems of rotary kiln, air.

Pre-operation Costs
 Capital Costs
 Operation, Maintenance & Closure
 Disposal Costs

A-1: Rotary Kiln, air	C-3: Plasma furnace, Steam Gasification
A-2: Rotary kiln, Oxygen	D-1: Fixed Hearth, O ₂ , CO ₂ retention
A-3: Rotary kiln, air, wet APC	E-1: Rotary kiln, air, thermal desorber
A-4: Rotary kiln, oxygen, CO ₂ retention	F-1: Molten Salt Oxidation
A-5: Rotary kiln, air, polymer stab.	G-1: Molten Metal Waste Destruction
A-6: Rotary kiln, O ₂ , max. recycling	H-1: Steam Gasification
A-7: Slagging rotary kiln	J-1: Joule Heated Vitrification
B-1: Pyrolyzer, oxygen	K-1: Mediated Electrochemical Oxidation
C-1: Plasma arc furnace	L-1: Super Critical Water Oxidation
C-2: Plasma furnace, O ₂ comb. & CO ₂ retention	

Figure 4-5. PLCC estimates for nineteen Phase 1 and Phase 2 ITTS systems (in thousands of dollars).

**SYSTEM TOTAL LIFE CYCLE COST AS A FUNCTION OF DISPOSAL COST
FOR A TREATABLE MLLW INVENTORY OF 236 MILLION LBS
(NO CREDIT FOR CONTAMINATED SOILS)**

Figure 4-6. System total life-cycle cost as a function of disposal cost.

LEGEND

- ◆ Studies, bench-scale tests and demonstration cost component
- Building cost component
- ▲ Equipment cost component
- Operations budget funded activities cost component
- Operation and maintenance cost component
- ▲ Decontamination and decommissioning cost component
- Disposal cost component

Figure 4-7. Results of sensitivity analysis.

Figure 4-8. Disposal Costs associated with the three stabilization options for rotary kiln using air (System A-1).

5. SYSTEMS EVALUATION

Evaluations are conducted at both the system and subsystem level. Evaluation at the system level includes reviewing the overall system concept against the treatment selection guides established in the Federal Facility Compliance Act of 1992 (FFCA).¹ The FFCA guides were developed to compare treatment options as part of the selection process for preferred treatment alternatives. The topics covered in these guides are:

- Regulatory Compliance
- Environmental, Health and Safety
- Treatment Effectiveness
- Implementability
- Stakeholder Concerns
- Life-Cycle Cost
- Technology Development.

Table 5-1 (page 5-41) lists the FFCA treatment selection ranking guides, which are discussed further in Section 5.1 as they apply to ITTS.

The goal of evaluating the systems is to qualitatively assess technology risks, including system maturity and developmental work needed to make the system ready for detailed design. Key issues related to system compliance are identified and discussed. Subsystems are evaluated against technology risks in the same manner as the systems, except that public acceptance is not considered for the subsystems. The systems and their subsystems are compared against the baseline system A-1 (rotary kiln, air) and its subsystems (see the Phase 1 report).

In the evaluations presented in this section, systems are considered for processing either alpha or nonalpha waste. The discussions apply to both waste categories except when a specific category is mentioned.

5.1 Technology Risk

In broad terms, evaluation of technology risk assesses the probability that the system or subsystem will meet the established objectives. The objectives are described below and are also listed in the "high score" column of the selection guides¹ of Table 5-1.

5.1.1 Regulatory Compliance

Treatment systems under consideration should be developed to ensure that the final waste form meets the land disposal restriction (LDR) standards and that the EPA and DOT regulatory

requirements, state and local laws, and other relevant requirements are met. Previously permitted technologies are considered more favorably than technologies that require regulatory exemptions or may encounter other permitting difficulties.

5.1.2 Environmental, Safety, and Health Objectives

Waste treatment operations should provide for the safety and health of the operational and construction/decommissioning workers and the public, and protection of the environment.

5.1.3 Evaluation for Treatment Effectiveness

The treatment effectiveness objective includes the following components: maximizing waste volume reduction; minimizing secondary waste generation; high efficiency for destruction, removal and/or demobilization of regulated compounds; flexible response to waste input variation; and final waste form performance to regulatory requirements. The technologies should be well developed and should provide reasonable assurance that the established requirements will be met (see Appendix A of the Phase 1 report). Compliance with these objectives is evaluated by reviewing the technology and hardware used. Areas of noncompliance or uncertainties are identified, and the need for further investigations, studies, and demonstration is stated.

5.1.4 Evaluation for Implementability

The implementability objective relates to the ease and likelihood of bringing a treatment technology into operation within the proposed schedule and cost. Implementability includes the following considerations: ability to build, construct or implement the treatment option; the mechanical availability estimated for the system; the ability to transfer the technology from bench-scale to full scale; and waste management scheduling concerns. Waste management scheduling assesses the time required to process the waste, including studies, design, demonstrations, construction, permitting, and the effect of facility capacity limitations.

5.1.5 Evaluation for Stakeholder Concerns

The technology should be received positively by stakeholders, who may include the local public, the public near the intermediate and final destination of the waste, state and local governments, Native Americans, Congress, and industry. Stakeholders should accept the process and the risks. The volume of offgas produced and the stability of the final waste form are addressed in the stakeholder concerns discussions, as these are issues of public concern.

5.1.6 Evaluation for Life-Cycle Cost

Technologies should have reasonable costs and a low probability of cost overruns. Life-cycle costs should be supported within a target budget. Systems that have never been constructed are assumed to have a high probability of cost overruns.

5.1.7 Evaluation for Technology Development

The technologies should be fully developed and ready for starting detailed design by 1996. Markets for the technology are identified both within and outside DOE.

5.2 Evaluation of the Baseline System, Rotary Kiln, Air (System A-1)

The baseline system (A-1) uses well-developed commercial technologies. A majority of the components have been previously used in hazardous waste applications and are available from several vendors. The system has twelve major subsystems.

The receiving and preparation subsystem uses SGS and PAN assay units, an RTR inspection unit, gantry robots, hydraulic and master-slave manipulators, sorting tables, and remotely operated vehicles.

Key technologies used for the incineration and APC subsystems are a rotary kiln incinerator; a dry offgas unit equipped with a quench, a baghouse, mercury removal activated carbon absorbers, and HEPA filter scrubbers; and a wet offgas unit equipped with a hydrosonic scrubber and packed tower acid-gas scrubbers.

The lead recovery subsystem uses mechanical tools, decontamination booths, and a melter equipped with a standard dry APC.

The amalgamation subsystem uses a vacuum retort with a mercury condenser and separator, a secondary combustion unit with a standard dry APC train, and an amalgamation reactor.

The metal decontamination subsystem uses an abrasive blasting booth. The metal melting subsystem uses an induction melter with a dry APC unit.

The aqueous waste treatment subsystem uses commercially available precipitators, solids filters, ion-exchange vessels, carbon filters, and evaporators.

The primary stabilization system uses a melter with a standard dry APC unit for vitrification of bottom ash and fly ash. A specific melter type is not specified at this time. However, for estimating purposes, costs for a centrifugal hearth plasma melter were used.

The secondary stabilization system uses commercially-available dryers and extruders to dry the incoming waste and mix it with polymer.

5.2.1 System Technology Risks

In the evaluations presented below, the system is considered for processing either alpha or nonalpha MLLW.

5.2.1.1. Regulatory Compliance. Rotary kilns are a commercial technology, permitted for facilities throughout the United States. Rotary kiln incinerators using APCs similar to those in the baseline system have been previously permitted under RCRA, CAA, and many state and local

regulations. The system is designed to meet the TSCA performance standards established for polychlorinated biphenyls (PCBs). Components essential to achieving the required performance (the secondary combustion chamber and the APC subsystem) have successfully been used in previous applications for destroying PCBs. The final, vitrified, waste form is expected to meet LDR requirements.

5.2.1.2 Evaluation for Environmental, Safety and Health Objectives. The alpha cell concept is expected to assure that the environmental, health, and safety objectives will be met when processing alpha waste. For nonalpha MLLW, the ES&H objectives can be met by reducing confinement to one or two levels, depending on the potential for release of radioactivity to the environment.

Three main ES&H concerns are the compliance with emission limits, acceptability of the rotary kiln, and the volatilization of actinides when processing alpha MLLW. These three issues are discussed below.

5.2.1.2.1 Compliance with proposed emission limits—Although it is expected that the system will ultimately meet the proposed emission standards given in Section 1, and in Appendix A of the Phase 1 report, several areas could require further development, demonstration, and testing. These areas are discussed below.

- **Mercury removal.** The thermal treatment and APC design strategy for mercury removal is to minimize mercury in the fly ash and the scrubbing liquor (mercury contamination in the fly ash complicates its stabilization by vitrification, and mercury contamination in the scrubber liquor will result in extra steps in the aqueous waste treatment). In following this strategy, a carbon bed filter is placed downstream of the baghouse to capture the mercury in the dry offgas. The activated carbon bed is impregnated with various materials (e.g., sulfur) to remove up to 90% of the mercury in the dry offgas. However, in order to verify the effectiveness of this process, two specific design problems must be resolved through further design studies, development, or process demonstration. These two areas consist of (1) cooling the gas to about 150°F just before carbon filtration, and (2) removing condensate in the flue gas just before the HEPA filters.
- **Lead removal.** Both organic and inorganic lead compounds are expected to be volatilized during thermal destruction in the incinerator. The APC system does not have any specific feature for lead removal. Preliminary reviews indicate that lead and its compounds will be removed either in the baghouse or by the scrubbers. EPA has put emphasis on reducing airborne lead discharged from incinerators. Acurex Environmental Corporation recently tested trace metals distribution for the EPA at the Incineration Research Facility using various APC equipment configurations. The studies showed that the fraction of lead in scrubber exit flue gas could range from 5% to 80% of the input. Additional efforts are needed to study the fate of lead compounds in the APC. The investigations should facilitate development of design options for high lead removal efficiencies.
- **Actinides.** The actinide volatility and removal efficiency are not known for various APC designs, and further studies and demonstrations may be needed. To comply with health and safety standards, the concentrations of the actinides discharged from the APCs must be

extremely low and perhaps even below detection limits. Preliminary studies show that most of the actinides in the incoming waste stream will remain with the bottom ash. A small fraction could volatilize^j or be entrained in the incinerator unit and exhausted to the offgas train, where it is separated along with the fly ash. Actinides could once again volatilize when the bottom ash and fly ash are stabilized in the vitrifier. Studies have also indicated that when combined with aluminosilicates, actinide volatility may decrease. Actinide volatility in complex mixtures of ash and soil are unknown but will be lower than for pure substances.

- **Dioxins.** Wastes containing dioxins or furans are not included in the DOE waste inventories considered in this study. There are, however, conditions within the thermal treatment system that are conducive to the formation of dioxins. Limiting dioxin discharges to the atmosphere is, therefore, a two-step process. First, exposing products of incomplete combustion to conditions favorable to dioxin formation must be discouraged and, second, measures must be taken to capture those dioxins that are formed before they leave the system. Investigations have shown that dioxins are readily formed if products of incomplete combustion resulting from incineration are exposed for even short times to temperatures ranging between 400 and 600°F. As a consequence, the offgas leaving the secondary combustion chamber should be cooled through this range as quickly as possible. This is most efficiently accomplished using a direct contact cooler. In this system, a spray cooler is used to cool the offgas from about 2,200 to 350°F to avoid damage to the baghouse filter material and to minimize dioxin formation. In addition, this system includes a carbon absorber. While the main purpose for this carbon is mercury removal, it is quite possible that it would be able to remove dioxins. This should be investigated in more detail. Additionally, studies have been done indicating another method that could be used to inhibit the formation of both dioxins and furans. This method involves introducing sulfur into the hot offgas stream. This could easily be accomplished by using coal with a moderate sulfur content as an auxiliary fuel.
- **Oxides of nitrogen.** The combination of elevated temperatures, an oxidizing atmosphere, and extended residence time all favor the formation of oxides of nitrogen in the secondary combustion chamber. While the quantities of nitrogen oxides produced by the thermal treatment system will not exceed those of an average-sized industrial boiler, their abatement will have to be addressed. Technology to meet the current abatement

j. To provide a rough estimate of the level of the actinides to be removed by the incinerator and vitrifier APCs, a thermodynamic analysis of uranium (U), plutonium (Pu) and Americium (Am) volatilization was performed at LLNL (see Appendix F of the Phase 1 report). The results show that pure U, Pu, and Am volatilize in the incinerator secondary combustor at a temperature of 1,366 K and that the volatilization will increase as the quantities of chlorides and fluorides in the feed increase. The actinide concentrations in the incinerator offgas exhaust could range between 3.0×10^{-6} to 3.2×10^{-4} kg of actinide per kg of offgas for U, 2.1×10^{-9} to 3.2×10^{-7} for Pu, and 1.1×10^{-12} to 1.6×10^{-10} for Am. The actinide concentrations in the vitrifier offgas exhaust (with a melt temperature of 1,873 K), will be higher and could be about 6.0×10^{-3} kg of actinide per kg of offgas for U, 1.3×10^{-7} for Pu, and 6.5×10^{-11} for Am.

requirements is available on the commercial market. As the restrictions become greater, technology to meet the challenge will be developed to serve the fossil-fueled power industry.

5.2.1.2.2 Acceptability of rotary kiln for alpha MLLW—A kiln is a bulky piece of mechanical equipment with many rotating parts. Major maintenance (e.g., replacing refractory brick) could result in high worker exposure. A solution to this problem is to use designs that allow remote maintenance. Another concern about rotary kilns is leakage through the seals. Leakage from the seals could introduce alpha contamination in the alpha cell and cause further complications during maintenance. A solution to this is to place a secondary housing around the rotary kiln seal (these devices are commercially available). Another solution is to increase the volume of the kiln to about twice the normal size so that combustion excursions can be tolerated with minimal leakage outside. Yet another concept that will reduce excursions is fine shredding and mixing to produce a continuous homogenous feed stream. All three of these strategies can be employed to reduce risks to a minimum. In addition to the reduction in puffs from operation, the same strategies will increase refractory lifetime.

5.2.1.2.3 Actinide volatilization—Actinide volatilization and potential release to the atmosphere is the greatest ES&H concern for the system when it is used for alpha MLLW. Because of the presence of the toxic radionuclides uranium, plutonium, and americium, even a small quantity of actinide release through the stack could cause concern regarding public exposure. This area must be studied further as indicated earlier in this section.

5.2.1.3 Evaluation for Treatment Effectiveness. Although technologies used in the system are well developed, there are some system-wide design concerns that require resolution through additional studies and engineering development (some might also require demonstration). These concerns are not considered to be detrimental to the system effectiveness, and there is a high probability that they can be satisfactorily resolved through system engineering (i.e., investigation of alternatives) and developmental efforts. Areas of concerns are discussed below.

5.2.1.3.1 Soundness of the concept for mercury management—The concept for managing mercury is untested. Two crucial parameters, level of mercury contamination in the feedstock and the removal efficiency of the activated carbon filters, are not known at this time. The system strategy for managing mercury is to remove all elemental bulk mercury or any bulk mercury compounds and to feed remaining mercury-contaminated waste to the incinerator unit. In the incinerator, mercury volatilizes and flows with the offgas to the APC. The mercury is then captured by activated carbon filters. Once the removal efficiency of the activated carbon filters under system conditions are known, the maximum allowable mercury in the feedstock can be defined. Current DOE waste inventory data indicate that a large part of the inventory has mercury contamination but very little is known about the concentrations. This introduces a high level of uncertainty regarding the quantity of mercury contamination allowable in the incinerator feedstock. The exact design of the system for managing mercury may not be known until more details on the concentrations are available.

5.2.1.3.2 Temperature profile to achieve optimum performance—The temperature profiles for the incinerator and the APC train require further studies. The temperature profile is critical in minimizing dioxin formation, mercury management, and RCRA metals removal strategies.

5.2.1.4 Evaluation for Implementability. The rotary kiln incinerator is a commercial technology for hazardous waste and is currently employed at ORNL. Key areas to be evaluated are improvements to rotary seals and refractory lining life. Advanced, commercially available seals have not been used in this application. Rotary kilns are large, mechanically complex machines. Developmental work to improve reliability and maintainability might be needed.

The facility design concept, discussed below, may require some refinement to maximize implementability. Another area for concern is characterization of the waste.

5.2.1.4.1 Compliance with the facility design requirements—The system complies with a majority of the design requirements. A major area of concern is the design for alpha confinement. Further studies are needed to refine facility layout concepts and confinement levels in the process, maintenance, and operating areas for treating alpha MLLW. Two or three levels of confinement are needed when processing alpha MLLW. The concept used in the preconceptual system layouts is based on placing equipment in air-tight cells that have three levels of confinement. Personnel access to the cells is through airlock doors. Personnel entering alpha cells must wear Level A protective equipment, including self-contained breathing equipment. Large corridors are provided next to each cell for equipment pull-out and maintenance. In this corridor, major equipment is disassembled and decontaminated (if required) so that it can be sent to the maintenance shop for further repair. This confinement approach has seldom been used by DOE, and further evaluation is needed.

5.2.1.4.2 Waste characterization—The feedstock characterization unit proposed for this system needs engineering development. The current approach to characterization is based on using two specific sets of components. The first set consists of a remotely operated on-line grab sampler that is mounted at the shredder discharge port. The sample obtained by the grab sampler is remotely sealed and sent to an analytical laboratory by a pneumatic tube conveyor. The second set of components includes a number of transportable hoppers and an incinerator feeder that control the transportation and feeding sequence of the waste after it is characterized. Each hopper has a storage capacity equal to 1 hour's production of shredded feedstock (approximately 2,000 lbs). Each hopper has a fill port on top and a dump port in the bottom. The hoppers collect waste from the shredder, and a crane transports the filled hopper to a storage area or to the incinerator feeder. The on-line sampler provides several grab samples before waste is discharged from the shredder to each hopper. The characteristics of waste in each hopper are determined by analytical testing of the samples. Once the waste characteristics are known, the operator will be able to accept or reject the waste in the hopper. This concept, which has not been tested before, will require further engineering development and demonstration to allow integrating the characterization concept into the overall system design.

5.2.1.5 Evaluation for Stakeholder Concerns. This system includes a state-of-the-art APC subsystem that has high decontamination and removal efficiencies. A rotary kiln incinerator is already in operation at ORNL. The Consolidated Incineration Facility at the Savannah River Site is also based on a rotary kiln incinerator concept. This past experience should help the subsystem gain acceptance by the public and permitting agencies. Another factor that might help in gaining public acceptance is the leach-resistant, high-integrity waste form produced by this system. This waste form will prevent release of hazardous material to groundwater over the long term. However, it should be recognized that, in general, the public and state and local permitting agencies are not receptive to incinerators. Siting selection for an incinerator is a critical element affecting success.

5.2.1.6 Evaluation for Life-Cycle Cost. When applied to nonalpha MLLW, the cost risk is low because of previous use of this system for this type of waste. However, the risk of cost overruns when the system is applied to alpha MLLW (plutonium) is high. This is largely because most system components must be further developed to allow ease of decontamination and maintenance for application in an alpha cell environment.

5.2.1.7 Evaluation for Technology Development. The baseline system employs conventional technology and is expected to be ready for detailed design within the specified schedule. Significant developmental problems resulting in long delays are not expected. Markets for the incineration technology exist commercially as well as within DOE.

5.2.2 Subsystem Technology Risks

5.2.2.1 Receiving and Preparation Subsystem. The receiving and preparation subsystem has three major functions: (1) waste package receiving and unloading from the incoming vehicles; (2) assay and nondestructive examination of the incoming containers; and (3) decapping, dumping, and sorting of the waste containers. The latter two functions will require extensive system concept development, component development, hardware engineering, and system integration. Consequently, there are moderate technical, ES&H, cost, and schedule risks associated with this subsystem.

The first function, receiving and unloading, can be accomplished by well-known designs and commercially available equipment. The remaining two functions, assay and nondestructive examination, and decapping, dumping and sorting, will require further development, particularly when the facility is used for alpha MLLW.^k Systems engineering and integration and hardware development are needed. The sorting operation will require extensive development. The preconceptual design presented in this study is based on robotic sorting, which has not been tested. Manual sorting and automated sorting devices (e.g., trommels, air classifiers, eddy current devices, magnetic separators) need examination and evaluation.

If this preconceptual design is to be successful in achieving the intended goals, the hardware listed below must be developed and tested for use in the intended system environment.

- **Real-time radiography.** State-of-the art RTRs have been used on an experimental basis at the Radioactive Waste Management Complex (RWMC) at INEL. Suggested development needs are enhancement of the RTR design and assessment of the data interpretations based on the experience gained at INEL.
- **Alpha-radiation assay.** Alpha radiation detectors based on PAN assay devices are the current technology base for DOE facilities. The PAN device, while suitable for TRU waste (> 100 nCi/g), has questionable accuracy at lower ranges of alpha contamination.

k. The Hanford waste receiving and packaging facility and the INEL waste characterization facility projects, which are in Title I and II design stages, have already done engineering development work on most of the components needed for accomplishing the functions of this subsystem.

- **Sorting table.** A rotary table suitable for manipulator sorting (for alpha MLLW) or hand sorting (for nonalpha LLW) is proposed. The manipulator sorting concept, which has not been used before or tested on wastes with the anticipated levels of contamination, will require engineering development.
- **Container decapping device.** For alpha MLLW, remote decapping of the containers is desirable. Manual decapping could become labor intensive since the operators would have to wear personal protective equipment with self-contained breathing apparatus. To develop a remote decapping system, engineering review of various options and selection of a workable concept for the intended application is needed.

Figure 2-2 notes components that are commercially available but require engineering development and demonstration on a system integration level.

5.2.2.2 Incineration Subsystem. The incineration subsystem has three major functions: waste preparation, characterization, and incineration. When used for nonalpha MLLW, these functions can be accomplished by well-developed, commercially-available technologies. However, equipment engineering development work will be needed when the subsystem is used for alpha MLLW. Hence, the technology risk for this subsystem is judged to be low when it is used for processing nonalpha MLLW and moderate when used for alpha MLLW. Figure 2-5 notes components that are commercially available but require engineering development and demonstration on a system integration level. Some of the developmental needs for this subsystem are discussed below.

5.2.2.2.1 Shredders and other feed preparation equipment—Since a rotary kiln is an adaptable incinerator that can accept both combustible and noncombustible waste, its feed preparation needs are minimal. A single-stage low-speed shredder (KOMAR) can provide the required preparation function. However, large shredders are mechanically complex and will require frequent maintenance and upkeep. This presents some problems for the subsystem when it is used for alpha MLLW. Another concern is the potential for fire in the shredder, which might require using a blanket of inert gas inside the shredder housing. Hence, developmental work to improve equipment safety, reliability, and maintainability is needed.

5.2.2.2.2 Solids separation—The current design concept for the system is to minimize upfront sorting by feeding the intact containers (drums or boxes) directly to the shredder unit. After shredding, the entire waste, consisting of combustible and noncombustible material (e.g., soil, metals) is fed to the rotary kiln. An alternative to this approach could be some amount of post-shredder sorting to recover metals. This would require using additional in-cell solids separation and material handling equipment (e.g., magnetic belts, eddy current devices), which are not desirable when the subsystem is used for alpha waste. However, for nonalpha MLLW there may be some advantages to metal recovery, and this alternative should be investigated further.

5.2.2.2.3 Characterization—A method for characterizing the incinerator feed was discussed under the system development needs in the previous subsections. As indicated, this concept must be developed further. A characterization concept for bottom ash may also be needed, since it appears that knowledge of ash properties, particularly carbon content, may be needed to determine the appropriate stabilization technology.

5.2.2.2.4 Rotary kiln incinerators—Although rotary kiln incineration technology is well developed, some areas could be further improved to enhance ease of maintenance and operation. This is especially true when the subsystem is specified for processing alpha MLLW.

There are two basic concerns regarding rotary kilns: 1) the potential for uncontrolled air leakage that would result in contamination spread from puffs (over-pressure events) during processing of radioactive waste, and 2) kiln refractory lining, which needs very frequent replacement. These two concerns are discussed below.

Air leakage through the rotating seal is a technical concern. However, with kiln seal designs available in today's marketplace, leakage is very controllable. Most kiln manufacturers offer seals that have a sliding graphite/steel interface, which provides a very leak-tight operation. Maintenance of these seals, at least in one instance known to the authors, has been low. At the Dow Chemical Corporation rotary kiln in Texas, such seals have been in operation for several years without requiring replacement.

The other part of the potential leakage concern is related to the waste feed process. Nonuniform feeding of the waste stream, i.e., bulk feeding of drums of liquids or waste with high heat content, causes puffs. If liquid waste is metered steadily, and if solids are shredded and fed continuously, puffs do not occur. In summary, this concern is probably avoidable by selecting an appropriate seal system and by improved operational practices.

The refractory maintenance concern can also be resolved satisfactorily. Factors affecting refractory lifetime are primarily 1) material selection, and 2) kiln operations. Careful selection of high quality (high cost) refractory is the first requirement for a reasonable refractory lifetime of several years. However, the best refractory will have a poor lifetime unless careful operating practices are observed that minimize rapid and frequent heat-up and cool-down cycles. Bulk feeding of drums and other large waste objects also contributes to reduced refractory lifetime, but less so than does thermal cycling.

Consequently, a premise has been made for this study that all solid wastes will be shredded to minimize refractory damage and puffs. Liquid will be combusted in a liquid burner rather than being fed in bulk.

With attention paid to these concerns, these technical issues appear to be resolvable by system design and good operating practices. Some commercial incinerator operators follow such practices and others do not. Their choice is based on their economic situation. For a DOE facility, it is believed that good design and operating practices could provide low system maintenance costs.

5.2.2.3 Incineration APC Subsystem. Most of the equipment (except monitoring equipment) used in this subsystem is well developed and widely used in industry. However, the subsystem will require extensive development for system integration. The subsystem is designed for highly efficient removal of pollutants. This is provided by using a complex set of state-of-the-art air pollution control equipment. The performance of the design should be verified and enhanced through large-scale demonstration units.

The incineration APC subsystem has to remove four major types of pollutants from the incineration offgas: particulates, acid gas, RCRA metals, and radioactivity. The APC is the most important unit in the system. It must ensure that offgas released to the environment has minimal pollution. Although the proposed design is believed to be state-of-the art with high efficiency contaminant removal, several areas will need further studies and development before the final system design can be finalized. Figure 2-7 notes components that are commercially available but require engineering development and demonstration on a system integration level.

5.2.2.3.1 Induced fan limitations—An additional booster fan may be needed at the midpoint of the APC subsystem. Because the APC has numerous components, the pressure drop across the treatment train may exceed the capability of a single induced-draft fan.

5.2.2.3.2 Temperature limitations of baghouse units in the APC subsystem—The APC subsystem operating strategy of preventing mercury contamination in fly ash may not be practical, because the gas must be cooled to meet the low temperature limitations of baghouse units, where the fly ash is filtered out. At temperature ranges of 400–450°F (the upper limit for typical baghouses), it is possible that some mercury will condense and drop out in the baghouse, thus contaminating the fly ash. This can be resolved by filtering out the fly ash at higher temperatures, well above the mercury condensation temperature. German and Japanese incinerators use high-temperature baghouses² and ceramic filters for this purpose. Further efforts are needed to resolve this concern.

5.2.2.3.3 Temperature limitations of activated carbon filters for removing mercury—Design concerns regarding mercury-removal filters center around low offgas temperatures (150°F) required by activated carbon filters. The concerns are mostly due to complications from the additional step needed to cool the offgas before it enters the filters. Some potential problems include corrosion of the offgas cooling equipment and the effect of condensates on HEPA filtration. A potential solution is to install a shell-and-tube heat exchanger after the baghouse. To eliminate water in the HEPA filter, the offgas could be reheated. Pending further studies, these solutions have not been incorporated in the present system preconceptual design.

5.2.2.3.4 Stack discharge monitoring equipment—A real-time monitoring system must be developed to measure both RCRA metals and radioactive species leaving the stack. As stated previously, the public and regulatory agencies put great emphasis on this feature of the system. Real-time monitoring allows system shut-down in the event of malfunction, thus preventing uncontrolled release of pollutants.

5.2.2.3.5 Back-flushable stainless steel HEPA filters—Back-flushable stainless steel HEPA filter technologies have been developed at DOE's Lawrence Livermore National Laboratory. Applying this technology to a high-level waste vitrification furnace is being investigated at Hanford Site. Similar investigations are needed for using stainless steel HEPA filters in the incineration APC subsystem. Additionally, the potential for corrosion in the stainless steel HEPA filters needs investigation. Alternative materials of construction should be studied.

5.2.2.4 Lead Recovery Subsystem. Most of the equipment used in the lead recovery subsystem is well developed and widely used in industry. However, the subsystem will require minor development to permit system integration. The lead recovery subsystem is designed for removing

radioactivity, in slag form, from contaminated lead. This approach will require process studies and some bench-scale development work. The overall technology risk for this subsystem is judged to be low.

Many of the development efforts recommended for the incineration APC are also recommended for the lead recovery subsystem APC. Other areas of development for this subsystem are treatment of lead gloves and system integration. Figure 2-8 notes components that are commercially available but require engineering development and demonstration on a system integration level.

Lead gloves are made of lead wool or thin layers of lead and synthetic rubber. The current APC system for the lead furnace does not have acid removal (scrubber) capability. Therefore, the system design may have to be modified to allow treatment of lead gloves.

5.2.2.5 Mercury Amalgamation Subsystem. Mercury recovery, recycling, and amalgamation are commercially available processes. The equipment used for this application is well developed and widely used in the industry. Hence, the overall technology risk for this subsystem is judged to be low.

The subsystem employs a retort that is used to vaporize mercury in a vacuum. The vaporized mercury is condensed in the offgas condenser and removed in a separator column. Any organic compounds vaporized in the vacuum furnace are also condensed in the condenser and removed separately. The condensed organics can be sent for thermal destruction by the incineration subsystem.

The primary developmental need for this system is system integration. Figure 2-10 notes components that are commercially available but require engineering development and demonstration on a system integration level.

5.2.2.6 Metal Decontamination Subsystem. The metal decontamination subsystem uses an abrasive blasting booth to remove surface contamination. This technology is well developed and many units are currently in use by the nuclear industry. Hence, the technology risk associated with this subsystem is low. Only some of the equipment in the subsystem requires development in terms of system integration (see Figure 2-12).

5.2.2.7 Metal Melting Subsystem. The input waste feed rate to the metal melting subsystem is very small. Hence, the need for this subsystem is in question. This subsystem could be viable if a single unit with equipment for fabrication of recovered steel is built for the entire DOE Complex. The recovered metal can be recycled by fabricating it into containers that are reused at the facility. Such an option needs further evaluation, taking into account the cost savings from recycling versus the capital and operating costs.

The subsystem uses an induction furnace to melt the metals. Various fluxes are used to force radioactive isotopes into a slag phase. This approach decontaminates metals to a level that allows recycle and reuse. However, the use of fluxing agents needs further bench-scale testing and development.

Equipment used for metal melting is well developed, and two units are known to be in use in the United States and Germany. In the U.S., SEG is recycling steel for DOE. The German facility, Simplekemp, recycles the metal for use as waste containers. Hence, the technology risk associated with this subsystem is low. Only some of the equipment in the subsystem requires development in terms of system integration (see Figure 2-14).

5.2.2.8 Special Waste Treatment Subsystem. Equipment used in the special waste treatment subsystem will be designed and developed on a case-by-case basis. A detailed listing of the waste types must be obtained, and potential process applications must be studied as part of future tasks. The potential waste stream to be treated by this subsystem is reactive metal wastes, such as sodium-contaminated debris.

5.2.2.9 Aqueous-Waste Treatment Subsystem. The aqueous-waste treatment subsystem uses commercially available processes and equipment. Development needs for this subsystem are minor. As a whole, the technology risk for this subsystem is judged to be low.

The preconceptual design strategy for mercury removal for this subsystem is precipitation and filtration followed by removal of trace mercury by ion-exchange resins or activated carbon beds. This approach must be finalized on the basis of more accurate knowledge of input waste properties.

5.2.2.10 Primary Stabilization Subsystem. The primary stabilization subsystem converts the incoming ash into a vitrified glass, rock, or ceramic. There are minor technical uncertainties associated with the subsystem. The technology risk associated with this subsystem is judged to be moderate. Figure 2-18 notes components that are commercially available but require engineering development and demonstration on a system integration level. Key developmental needs are discussed below.

5.2.2.10.1 Melt chemistry and vitrification formulations—Developmental work involving melt chemistry, thermodynamics, and waste formulation is underway at INEL. These efforts are aimed at a better understanding of the vitrification technology and optimization of the process. The efforts at INEL have yielded promising results including several high-integrity, leach-resistant melt formulas. The experimental work must be carried to a large-scale prototype unit.

5.2.2.10.2 Melter furnace design—The proposed melter technology in this study is a plasma arc furnace. Other studies have selected different technologies, such as Joule melters or electric arc furnaces. Melter design must be finalized, and efforts on equipment enhancement for safety, reliability, maintainability, and system integration must be started. Pilot-scale testing is needed.

5.2.2.10.3 Capturing volatilized metals and actinides—A method to prevent the flow of volatilized metals and actinides to the melter offgas unit must be developed. In this study, a moving sand filter serving as a cold trap is proposed for installation above the melter cap, at the offgas intake duct. The filter absorbs the volatilized metals. When the filter sand needs replacement, it is dumped into the furnace where it is vitrified with the waste. This method and other options must be studied further and tested on a bench-scale or in prototype test units.

5.2.2.10.4 Impact of carbon in ash—Bench-scale tests are needed to define the upper limit of carbon content in the ash and the effect of high carbon ash on the vitrification process and the resultant waste form.

5.2.2.11 Secondary Stabilization Subsystem. The secondary stabilization subsystem uses a polymer agent for stabilizing salts recovered in the offgas scrubber. Developmental needs include selecting a suitable polymer agent that can stabilize the salt and pass the TCLP tests. The subsystem uses commercially-available equipment. Hence, the technology risk associated with this subsystem is judged to be low.

5.2.2.12 Certify And Ship Subsystem. The certify and ship subsystem uses commercially available equipment except for the assay unit. The developmental need for the assay unit is the same as that for the assay unit in the receiving and preparation subsystem. The technology risk associated with this subsystem is judged to be low.

5.3 Evaluation of Slagging Rotary Kiln (System A-7)

The slagging rotary kiln system takes advantage of high temperatures to achieve more complete combustion than System A-1 (rotary kiln, air). The slagging kiln produces a low leachability solid requiring minimal further processing. There is a need for highly durable refractory lining for the high-temperature (e.g., 2500°F) incinerator. Incineration takes place in a slightly negative-air-pressure environment (pressure of about 1 inch of water). Typical temperature ranges for the slagging kiln are 1500 to 2600°F, compared to typical ranges of 1200 to 1500°F for an ashing kiln.

5.3.1 System Technology Risks

The system has a similar technology risk to the baseline system, aside from some unique risks.

5.3.1.1 Regulatory Compliance. Rotary kilns are a commercial technology, permitted for facilities throughout the United States and in widespread use in Europe. Process-related regulations can be met through standard permitting processes. The final waste form is expected to meet or exceed LDR standards.

5.3.1.2 Evaluation for Environmental, Safety and Health Objectives. The ES&H concerns are similar to those for the baseline system. As discussed in Section 5.2.1.5, the quality of emissions is expected to be better and the process control more dependable. Worker exposure in this system is reduced compared to the baseline due to elimination of the vitrification stabilization subsystem. In this system and the baseline system, risks to operational workers are increased if air outleakage from the kiln seals is not properly controlled.

5.3.1.3 Evaluation for Treatment Effectiveness. Key rotary kiln issues described for the baseline system, control of air leakage and kiln refractory lining maintenance, are applicable to the slagging rotary kiln as well.

Another issue is the nature of the final waste form produced by the slagging kiln. In hazardous waste applications, the slag produced has not always been a consistent, leach-resistant product. However, at one major kiln visited, minimal effort is expended to optimize the slag characteristics. Leachability testing and evaluation of the slag is necessary to assess the need for further stabilization. In the DOE MLLW application, the system concept depends on adding a continuous feed of glass-forming solids. This should provide a consistent, leach-resistant product.

Research programs at INEL have established that, for systems that will operate at 2650°F or above, excellent leach resistance is obtained with soil added to the waste residues in quantities ranging from about 40% to 60% by dry weight.⁷ For this study, in all systems producing a glass-ceramic waste form, a soil addition of 50% is assumed. Since the reasonable maximum temperature for a slagging rotary kiln is 2600°F, a fluxing agent will be needed to get the soil to melt. The quality of such a waste form is expected to be far superior to slag produced by commercial hazardous waste processors. However, this remains to be demonstrated and some development work will be required to establish the proper feed and the slag leaching characteristics.

5.3.1.4 Evaluation for Implementability. The slagging kiln is a well-developed commercial technology, with many hazardous waste units operating in the United States and Europe. The slag removal approach used in this design has had minimal commercial development. Slag management, viscosity control, and metals volatilization are the key issues requiring further development. System availability is expected to be predictably high based on extensive commercial use of kiln technology. Although both ashing and slagging kilns are mechanically complex, the process is simple and flexible. The need for scheduling waste into "campaigns" of similar materials is minimized compared to less flexible systems.

5.3.1.5 Evaluation for Stakeholder Concerns. Offgas generated in the slagging kiln contains fewer contaminants than that produced in an ashing rotary kiln. Waste in the slagging kiln has a longer residence time than in an ashing kiln because of the time required to allow the slag to form. Therefore, thermal inertia is greater and the process is less sensitive to thermal peaks due to variations in the feed. Destruction removal efficiency is increased due to both the higher temperatures and the longer residence time. The slagging kiln is effective in destruction of PCBs. Particulate loading in the offgas is reduced compared to an ashing kiln because of the higher thermal efficiency. Reduced particulate loading reduces the available sites for the formation of dioxins. The slagging kiln is more thermally efficient because the exothermic reactions of the waste reduce the heat input required. In an ashing kiln, cooling water is added to control heat produced by exothermic reactions that would raise the temperature above the design values. The higher operating temperature of the slagging kiln allows higher utilization of the heat generated by the combusting waste.

Depending on the calorific value of the incoming feed, the volume of offgas discharged to the atmosphere may be slightly greater or slightly less than that of the baseline system due to the higher operating temperature. The volume of offgas generated from a rotary kiln using air (slagging or ashing) is much larger than from alternative technologies (Table 3-11). The improved thermal efficiency of the slagging kiln and the elimination of the need for a separate vitrification process should make this system more acceptable to the public and regulatory agencies than the baseline system.

5.3.1.6 Evaluation for Life-Cycle Cost. The slagging rotary kiln is a commercial technology with well established costs.

5.3.1.7 Evaluation for Technology Development. Numerous markets have been developed for slagging rotary kiln technology. Slagging units are more frequently ordered than ashing kilns, according to one vendor. Design of a kiln for this application could proceed immediately. There are minimal technology risks related cost or schedule overruns. As discussed above, operating conditions are probably more important than further technological development.

5.3.2 Subsystem Technology Risks

Technology risks associated with the subsystems are similar to those of the baseline system. The high-temperature operation of the rotary kiln in the slagging mode may reduce the life of the refractory lining. This could increase the maintenance cost of the slagging kiln compared to the baseline system. Slagging units can be operated with a skull of slag on the refractory that protects it and provides similar refractory lifetimes to an ashing system. Design of a dry slag removal system appropriate for MLLW might require additional development. The characteristics of slag produced by the slagging kiln treating the DOE's MLLW should be evaluated in pilot testing.

The main thermal treatment APC is the same as the baseline system, although it is slightly larger to accommodate increased offgas.

System components that are commercially available but require engineering development and demonstration on a system integration level are noted in Figures 2-1 and 2-2. The key area requiring engineering development is the slag discharge mechanism.

5.4 Evaluation of Plasma Furnace, CO₂ Retention (System C-2)

The plasma furnace, CO₂ retention system (System C-2) differs from the baseline system in three major ways: 1) it utilizes a plasma furnace instead of a rotary kiln as the main thermal treatment, 2) oxygen rather than air is used for combustion in the main and secondary combustion chambers, and 3) the air pollution control system is equipped to allow the recycling of the oxygen in the combustion offgas.

The plasma furnace technology is the same as in System C-1 (plasma furnace, Phase 1 report). The use of this versatile, high-temperature unit eliminates the need for a separate vitrification furnace because the plasma furnace produces a vitrified slag. The metal melting subsystem has been eliminated because the plasma furnace can also be used for metal melting.

The plasma furnace has the ability to control intake oxygen flow rates. This system uses oxygen instead of air in the reactor and as a torch gas. Following the secondary combustion chamber, the offgas passes through an APC. In the APC, the offgas passes through several separation steps where specific products or contaminants such as water, CO₂, acids, particulates, and mercury are removed. The remaining offgas stream, primarily oxygen, is then recycled to the plasma furnace to support combustion. An offgas side stream is bled off to keep the fraction of impurities, especially nitrogen, at a controlled level. CO₂ removed from the offgas is stored in delay tanks with the side stream gas

before discharge to the atmosphere. This system uses a centrifugal plasma furnace. A fixed hearth plasma furnace could have been employed instead with little impact to the costs or mass balance of the study.

5.4.1 System Technology Risks

The technology risk must be judged higher than that of the baseline system due to the lack of commercial experience, and due to technical issues related to the offgas recycling process. Control of the total system gas pressure, offgas recycling rates, oxygen supply rates, and real-time gas sampling and analysis contribute to the complexities inherent to this process. Short lifetimes for plasma torch electrodes in these systems is a major impediment to operational availability.

Another performance area that may become a problem is refractory lifetime. These plasma systems operate at the same or higher temperatures as a slagging rotary kiln; thus, corrosion issues should be just as severe. Since none of the plasma systems have operated for purposes other than short technology demonstrations, these refractories have not yet been observed over time. Thermal cycling of the refractory associated with shutdown for torch electrode replacement may be more severe than for a slagging kiln. Only operating experience will clearly establish whether refractory lifetime is an availability-limiting issue.

5.4.1.1 Regulatory Compliance. Plasma furnaces have been evaluated by the EPA. Permitting requirements are similar to those for an incinerator. The final waste form, a vitrified solid, is expected to exceed LDR requirements.

5.4.1.2 Evaluation for Environmental, Health and Safety. The APC subsystem provides oxygen recycling, CO₂ retention, and control of gases prior to discharge. This system is designed to test the offgas prior to release to the atmosphere, and to reprocess gas that does not meet specifications. This feature provides superior control over emissions.

Issues remain regarding the fate of metals in the offgas of a plasma furnace. While a plasma furnace system will have higher efficiency than the baseline system in destroying organic compounds, it complicates the management of volatilized metals. This is due to the high temperature created by the plasma arc. Developmental efforts are needed to determine the fate of vaporized metal in the APC and methods for capturing it. The potential for metal to plate out in the APC should be evaluated. Developmental efforts must also be directed to the volatilized actinides in the offgas. The combination of the plasma furnace and CO₂ retention adds to concerns over the fate of RCRA metals. Since the APC subsystem is based on dry filtration only, the metal is either absorbed in the lime bed, separated and removed with the condensed water, or recycled back to the furnace. It is not known if any of the metal compounds absorbed by the lime will become vaporized when the spent lime is calcined. More detailed evaluation of the metal-removal aspect of this system is needed.

If the CO₂ retention system operates properly, the overall system should provide substantially enhanced protection against inadvertent releases of regulated material.

Worker exposure is increased compared to the baseline system due to the size and complexity of the APC subsystem with CO₂ retention. Quantification of this is difficult.

5.4.1.3 Evaluation for Treatment Effectiveness. The principal technology risks in this system are found in the plasma furnace design, air leakage prevention, control of the CO₂ retention process, and in the offgas recycling approach. The performance of the plasma furnace with CO₂ retention has not been demonstrated.

The CO₂ retention system provides a mechanism for offgas recycling and for delayed offgas release. The system allows sampling of the offgas before discharge to the atmosphere or recycling. The recycling of treated offgas to the plasma furnace requires that air leakage into the system is minimized, and that buildup of inert gases in the treated offgas is avoided.

The vitrified solids generated in the plasma furnace provide an excellent stabilized waste form for final disposal. At INEL, iron-enriched basalt soil has been demonstrated to melt in a plasma furnace and form a vitrified product.³ The volume of wastes produced is increased compared to the baseline system due to the wastes generated in the CO₂ retention system.

5.4.1.4 Evaluation for Implementability. Availability, reliability, and development concerns for the plasma furnace focus on the plasma torch electrode. Current electrode lifetime in plasma torches used in the DOE-sponsored development programs is very poor (< 100 hours). While this does not compromise destruction efficiency, it does impact system availability. Furthermore, online electrode failure results in a water leak into the processing vessel, which may have certain safety implications.

Refractory lifetime may also become an important limitation as previously discussed. Current plasma systems have only operated for very short periods (tens to hundreds of hours). Refractory repair in these skull systems will probably require major equipment disassembly. Repair experience in a radioactively contaminated environment does not exist.

There are many aspects of the CO₂ retention system that will require further development. Examples include development of a main thermal treatment unit with near-zero in-leakage, development of methods for separating and releasing accumulated inert gases such as nitrogen, understanding the fate of radionuclides in the system, and development and integration of complex process controls. The availability of the APC subsystem will be affected negatively by the early state of development of the CO₂ retention system. The process and mechanical complexity is significantly increased over the baseline system due to the CO₂ retention system.

The plasma furnace produces a final waste form requiring minimal further processing. The vitrification subsystem required in the baseline system is eliminated.

5.4.1.5 Evaluation for Stakeholder Concerns. The offgas volume from the plasma furnace using oxygen combustion is considerably reduced over that of the baseline system. The offgas volume released to the atmosphere is further minimized by recycling most of the oxygen and removing water from the discharged offgas. Under ideal conditions, the volume of the offgas discharged to the atmosphere could be about one tenth of the volume discharged by the baseline system (Table 3-11) although the concentration of compounds released will increase. Moreover, the system holds the CO₂ gas for a specified period of time, allowing release to the atmosphere only after it is confirmed that it meets the discharge criteria. Hence, inadvertent release of pollutants to the

environment can be prevented. If found to be feasible, it is possible that the system will be received positively by the public and the state and local regulatory agencies.

5.4.1.6 Evaluation for Life-Cycle Cost Objectives. The CO₂ retention subsystem is in its infancy. Hence, the cost of the system, including the cost of disposing of the final waste, cannot be estimated accurately at this time. The CO₂ retention system adds to the cost for construction, operation, and disposal. The processing of lime and calcium carbonate increases the final waste volume.

5.4.1.7 Evaluation for Technology Development. The plasma furnace for waste destruction is in an advanced early stage of development at this time. Several vendors supply plasma furnaces for hazardous waste treatment, indicating that markets have been identified both within and outside DOE. Plasma vitrification is being developed to potentially treat alpha waste at INEL. Another full-scale facility for LLW is in the startup stage in Switzerland. The intensity of development work currently taking place indicates that plasma arc systems will be commercially available within the required ITTS time frame. As noted above, electrode lifetime continues to be a problem. The flexibility of the plasma furnace system and its compact configuration make it an ideal candidate for continued development.

The CO₂ retention subsystem will require a significant amount of process development. This concept has not been demonstrated on a full scale. Recent research by Argonne National Laboratory on the removal of CO₂ in closed loop off-gas treatment subsystems has studied aqueous-based absorbents such as monoethanolamine or potassium carbonate solutions instead of the dry lime-based absorbent approach discussed in this study.⁴ Equipment used in the APC subsystem is commercially available.

5.4.2 Subsystems Technology Risks

The technology risks associated with the subsystems are higher than in the baseline system. Plasma waste destruction appears simpler, in principle, than the rotary kiln used in the baseline system. However, the limited operational history of the plasma furnace with hazardous or nuclear wastes increases the technology risk. Electrode lifetime is a very limiting condition, resulting in substantial downtime for replacement. The centrifugal hearth plasma furnace has moving parts and complex seals. The feeding system to the plasma furnace is similar to that used in the baseline system. Effective control of air leakage must be maintained at the feed system for CO₂ retention to function. Development work on fixed hearth plasma furnaces sponsored by the DOE Mixed Waste Integrated Program offers the promised versatility of plasma processing with the simplicity of a fixed hearth. Refractory lifetimes have yet to be established. The waste form produced by the plasma furnace requires only cooling and packaging. A separate vitrification subsystem is not needed. Figures 2-27 and 2-28 show key areas regarding engineering development and demonstration on a system integration level.

5.4.2.1 Receiving and Preparation Subsystem. Compared with the baseline case, less rigorous sorting and size reduction are required for this system because the plasma furnace can accept bulk combustible and noncombustible materials.

5.4.2.2. Main Thermal Treatment Subsystem. Plasma systems appear simpler, in principle, than a rotary kiln as used in the baseline system. However, no system has yet operated for more than 100 hours on waste or surrogate waste materials. Electrode lifetime is a very limiting condition, resulting in substantial downtime for replacement. The DC torch is more complex than graphite carbon electrodes. Techniques for remote replacement of the electrode have been developed. Overall, the technology risk is higher than for the baseline system – at least until a system is operated for a few thousand hours with acceptably little downtime.

Although the plasma system considered for this system is a fixed hearth with few moving parts other than the torch, the same is not true for the centrifugal hearth melter proposed for Pit 9. That system has considerably more moving parts and complex seals. Again, operating lifetimes are very limited in waste applications.

Another key concern for the main thermal treatment system is the potential for air leakage into the plasma furnace. This potential is considerably less than the likely air leakage into a rotary kiln with dynamic seals at each end. Vendor tests have recently been performed to assess air in-leakage to a plasma furnace. The plasma furnace design includes a double-walled shell with water cooling in the annular space. Furnace seals to the atmosphere are made of common, dependable, low-temperature materials. Because in-leakage to the furnace occurs through the water-cooled annulus, leakage would be in the form of water rather than air. The airlock at the feed system must be designed to minimize air in-leakage. The effect, if any, of the recycling of cleaned offgas on process flexibility is not known.

5.4.2.3 Main Air Pollution Control Subsystem. The main component of the CO₂ retention process is a circulating fluidized bed of lime that absorbs carbon dioxide from the offgas stream, permitting delayed release of CO₂. This concept originated at Argonne National Laboratory. The APC equipment ahead of the fluidized bed is designed to remove radionuclides and mercury. Radionuclides and mercury remaining in the offgas and subsequently absorbed in the fluidized bed could then be released from the calciner. The potential for radioactive metals and mercury to be collected in lime should be assessed. The lime recycle process is accomplished by heating the spent lime (CaCO₃) in a calciner. This process will require further operating data to better assess the lime recycling efficiency. A low efficiency could significantly affect the volume of final waste requiring disposal. The potential for radionuclides and mercury to be released from the bed material in the calciner must be evaluated. Many areas will require development in a prototype environment before the feasibility of this process can be ascertained. Other CO₂ capture methods may also be suitable or superior to the lime-based process, as noted above. Detailed process selection for CO₂ capture was beyond the scope of this study.

5.5 Evaluation of Plasma Gasification (System C-3)

The plasma gasification system employs a different approach to a plasma furnace. Technology currently available uses a nontransferable direct current arc electrode containing both the anode and the cathode. The position of the electrode is fixed and the reactor hearth is stationary. In its current state of development, its application is focused on thermal destruction of medical waste. It is designed for waste streams with high organic content (90% organics). To apply this technology to MLLW with significant inorganic content, the technology vendor recommends using a reactor capable

of accommodating a large slag pool. Also, a transferred arc electrode is recommended. In this configuration the slag will act as the anode and the cathode would be moved around the reactor, contacting slag at multiple points. For reactors currently available for medical waste treatment, a chamber wall temperature of 3000°F and a gas temperature of 1800°F are achieved. Steam is used to provide the oxidant and reactant species, and to encourage the formation of carbon monoxide rather than carbon dioxide.

The main equipment difference between this plasma furnace reactor and that in Systems C-1 (plasma furnace) and C-2 (plasma furnace, CO₂ retention) is that this system uses a fixed hearth melting pot instead of a rotary pot. This fixed hearth melting pot requires a freeze valve or similar mechanism for discharging the vitrified solids from the reactor. In centrifugal melters such as that used for Systems C-1 and C-2, rotation of the pot is used to regulate flow of vitrified materials from the reactor. As noted in Section 5.3, rotating and fixed hearth systems have similar impacts on costs and mass balances.

The plasma gasification system differs from the baseline system in several important ways. The main thermal treatment subsystem has a plasma furnace using air for the torch gas and steam as the oxidant. The vitrifier furnace in the primary stabilization subsystem has been eliminated because the plasma furnace produces a vitrified slag. The slag is produced in the same furnace used to destroy organics and only packaging of the slag is required for primary stabilization. Offgas generated can be sent to a steam boiler for energy recovery or to thermal oxidation.

5.5.1 System Technology Risks

Overall, the risks must be judged higher than in the baseline system, based on the lack of commercial experience with System C-3. This system shares the same risks for the plasma furnace as Systems C-1 and C-2.

5.5.1.1 Regulatory Compliance. As a reforming process that does not use a flame or an SCC, plasma gasification could be classified as an industrial furnace and permitted under the regulations for boilers and industrial furnaces. Alternatively, this system could be permitted as a RCRA miscellaneous facility. The final waste form is expected to meet LDR requirements, based on vendor tests.

5.5.1.2 Evaluation For Environmental, Health, and Safety Objectives. A plasma furnace system will be equally or more efficient in destroying organic compounds than the baseline system. However, the management of volatilized metals is complicated by the use of this technology. This is due to the high temperature created by the plasma arc. This is further complicated by operating in a reducing mode, which, depending on the exact thermodynamic conditions, may result in reduction of metal oxides and volatilization of metals in the metallic rather than oxide form. Further evaluation of the fate of vaporized radioactive and nonradioactive metals in the APC is needed. Effective methods for their capture and removal from the offgas stream must be determined. Development efforts must also be extended to include the fate of volatilized actinides in the offgas and their abatement. The potential for deposition of metals under pyrophoric conditions in the APC should be evaluated. Emissions of nitrogen oxides and dioxins for this system should be less than for the baseline system,

as the reduced atmosphere discourages formation of these compounds. The volume of emissions is halved compared to the baseline system (Table 3-11). This system reduces worker exposure relative to the baseline system by eliminating the need for a separate vitrification unit.

5.5.1.3 Evaluation For Treatment Effectiveness. The principal technology risks in this system are found in the plasma furnace design, which must be adapted for the DOE's MLLW. Hydrogen and carbon monoxide gases, products of organic gasification, must be handled to avoid explosions and other safety risks.

The plasma gasification technology processes organics and inorganics in a controlled atmosphere. Organic destruction produces hydrogen and carbon monoxide gas. The reduced atmosphere is maintained by feeding a sufficient fraction of organics with the inorganics. Feed characterization requirements could be increased compared to the baseline system. The relationship of feed characterization, processing atmosphere, and solid residue must be developed for the DOE's MLLW.

The slag produced in a reducing atmosphere with primarily inorganic waste must be evaluated. Tests performed by the vendor on nonradioactive DOE weapons components indicated that a stable waste form can be achieved using their reactor. However, the processing atmosphere during these tests was not described. Testing of combined inorganic and organic DOE MLLW using plasma gasification is required to determine if the slag meets DOE objectives for stabilized waste.

5.5.1.4 Evaluation for Implementability. The plasma gasification approach must be evaluated for DOE's MLLW. Preliminary work has focused on organics, which generate the reforming atmosphere. The process control and feed characterization requirements to maintain a reduced atmosphere increase the complexity of an otherwise simple system. Also, electrode and refractory lifetime will affect availability of the plasma reactor.

This process has not been brought from demonstration testing to full-scale operation. Schedule objectives would be affected by the need for further research and development of this technology.

5.5.1.5 Evaluation for Life-Cycle Cost. Plasma gasification is not a commercial technology yet. Accurate costs cannot be developed for the technology at this stage.

5.5.1.6 Evaluation for Stakeholder Concerns. Plasma gasification employs a nonincineration approach to destroy organic compounds. The cleaned offgas is recyclable as a syngas. Over 1000 lb/hr of syngas are generated. The final waste form is a stable vitrified product. Public acceptance of this approach is expected to be better than for the baseline system.

5.5.1.7 Evaluation for Technology Development. The plasma gasification reactor is in an early stage of its development. This technology has not been commercially applied. A plasma reactor using steam gasification is being designed for a hospital with a feed rate of 1,000 lb/hr of waste. Although it would be possible to design and install the plasma reactor within the required time frame, it is not evident that the technology will be sufficiently developed to satisfy DOE's functional and operational requirements. To date, only pilot studies and research have been performed. Although research has been performed with a variety of waste types, including inorganic and metallic wastes, current development is focussed on medical waste applications. Further development using DOE's waste is necessary.

5.5.2 Subsystems Technology Risks

The technology risks associated with the subsystems are higher than in the baseline system. As discussed above, plasma gasification is not proven operationally for mixed organic and inorganic waste destruction, and electrode lifetime is expected to be very limited, resulting in frequent downtime and replacement. Limited production experience with a recently developed electrode for the aluminum industry suggests improvements in electrode lifetime are possible.

Steam plasma reactors are less well developed than some other plasma furnaces. Operational issues are not well understood because only prototypes and test units have been built to date. A design is in progress for a system to treat primarily organic medical waste. The experience with metals in this type of plasma reactor includes bench-scale tests, but is not extensive. The leachability of the slag produced in the reducing atmosphere, as well as air pollution control for metals, must be better understood to meet DOE's objectives. Figures 2-30 and 2-31 note components that are commercially available but require engineering development and demonstration on a system integration level.

The principal concern regarding the main thermal treatment subsystem is limited electrode life. Other concerns include process control, refractory lifetime, volatilization of metals, and generation of a stable slag waste form. Using the steam plasma reactor for primarily inorganic waste requires further development.

5.6 Evaluation of Molten Salt Oxidation (System F-1)

In the molten salt oxidation (MSO) system, combustible waste and air are combined in a bed of molten sodium carbonate. The molten salt bed serves three major functions: it provides a contact surface for oxidants and waste; it catalyzes oxidation reactions; and it neutralizes acids in the waste, HF, H₂SO₄, and HCL. Scrubbing of the acids in the molten salt bed eliminates the need for acid gas scrubbing in the APC.

Only combustible waste (about 33% of the total waste, see Table 3-1) is fed to the MSO reactor; noncombustible debris and other solid materials are pretreated and fed directly to the separate vitrifier in the primary stabilization subsystem. Because of the need for sorting the combustible from noncombustible material in the feedstock, a more extensive waste receiving and preparation subsystem must be provided.

5.6.1 System Technology Risks

The system has a greater technology risk than the baseline system. A thorough review of the state of MSO technology was conducted in October 1993 for the DOE.⁵

5.6.1.1 Regulatory Compliance. Molten salt oxidation technology has been developed over the last 30 years with limited commercial operation. Permitting is expected to be under industrial furnace or miscellaneous RCRA facilities. MSO is not known to have been previously permitted for waste treatment operations. The inorganic or noncombustible waste (Table 3-2) and the ash residues

from the MSO system are fed to a separate vitrification system that is expected to produce a vitrified solid meeting or exceeding LDR requirements.

5.6.1.2 Evaluation for Environmental, Health, and Safety Objectives. The MSO system should be equally or more efficient in destroying organic compounds than the baseline system. Small molten salt systems have been constructed and operated by the technology vendor, Oak Ridge National Laboratory and Lawrence Livermore National Laboratory. These MSO systems demonstrated destruction removal efficiency and emissions were assessed for various waste streams. The fate of radioactive metals in the reactor vessel must be evaluated. Emissions of nitrogen oxides are reduced compared to the baseline system because fewer are formed at the lower operating temperatures. The volume of emissions are halved compared to the baseline system (Table 3-11). This system increases worker exposure relative to the baseline system due to the increased waste separations and the addition of equipment for salt recycling. Without salt recycling, the discharged sodium carbonate volume requiring disposal would be very large due to the high ash content (approximately 15%) in the combustible waste stream.

5.6.1.3 Evaluation for Treatment Effectiveness. The molten salt oxidation process can only treat combustible waste, whereas the baseline system can accept as feedstock both combustible and noncombustible waste. Although MSO can process a variety of wastes, it is most efficient when only organic materials are processed. Molten salt oxidation requires significant development to refine waste handling, treatment, and disposal requirements. Corrosion problems with the reactor vessel have been a concern with some designs. An alumina-lined reactor vessel has been demonstrated to have improved corrosion resistance.

MSO is sensitive to the amount of inert materials in the feed because they increase melt viscosity, reducing mass transfer of oxygen and salt catalyst to the waste. A preliminary review of the combustible waste shows that the inorganic composition (e.g., clays and other filler material contained in plastics, paper, and other waste) could be as high as 16%. This means that the input combustible waste may already have an inorganic concentration near the 20% limit allowed for MSO. Because of the high volume of inert materials in the feed, a higher volume of molten salt must be withdrawn from the reactor vessel in a continuous stream to keep the inorganic or ash content below 20%. This increases the size of the salt recycle subsystem that separates the ash and the salt.

The recycle subsystem consists of several steps. The salt/ash mixture is dried and then dissolved in water. The salt solutions are filtered to remove the ash. The salt solution is sent to an evaporative crystallizer where sodium carbonate is separated and the crystallized salt is returned to the MSO reactor. The sodium chloride remains in the solution. The salt recycle subsystem must be designed to accept and process a sufficient volume of salt/ash mixture to maintain less than 20% inerts in the molten salt bed. Recycling of the aqueous streams within the salt recycle subsystem avoids generating aqueous waste.

Molten salt oxidation waste feed is limited to a waste particle size of 1/8 inch or smaller to facilitate feeding into the reactor and to improve the kinetics of the reactor. Molten salt is most effective with feed with a low inorganic content. The baseline system is more versatile and can accept a wide variety of waste types and sizes.

The technology vendor recommends eliminating the wet scrubber from the flowsheet in this study. The scrubber was included to remove salt fumes that may have escaped the baghouse. The removal of the fumes reduces the potential for corrosion in the APC system.

Since MSO is not effective in the processing of noncombustibles, this waste stream must be segregated at the sorting station and fed directly to a vitrification unit located in the primary stabilization subsystem. In this subsystem, feed material must be shredded and dried in a calciner to remove water vapor to provide a controllable feed to the vitrifier. The dryer offgas must be collected and, if necessary, routed to the APC. The dryer adds to the mechanical and control complexity of the system. Trace organic compounds and solids (e.g., plastics) in the noncombustible material could further complicate the dryer operations. Process control of the vitrifier operation could also become difficult if organics are introduced in the unit.

The ash from MSO is also sent to the vitrifier. Incomplete combustion of waste in the molten salt oxidation could result in a high-carbon ash. However, ceramics are considered to be a preferable approach to vitrification for producing a final waste form from MSO ash. Vitrification was used to minimize the final volume for disposal.

5.6.1.4 Evaluation for Implementability. The MSO system employs a commercial technology that is available from at least one vendor. Constructing and implementing this system is expected to be more difficult than the baseline system. System availability is expected to be less than the baseline system due to the increased operational and mechanical complexity and increased characterization needs.

5.6.1.5 Evaluation for Stakeholder Concerns. MSO collects radionuclides by physicochemical methods rather than only by mechanical means as in the baseline system. Heavy metals are retained in a manageable salt matrix. These aspects of the technology may result in better acceptance of the thermal treatment facility by the public and the state and regulatory agencies. Since chlorides are retained in the bed, the system may have a lower propensity for formation of dioxins in the APC system than the baseline system.

5.6.1.6 Evaluation for Life-Cycle Cost. MSO is a commercially available technology, although there is limited commercial experience on wastes. Further development will be necessary to evaluate treatment of MLLW. MSO may not meet DOE's cost and schedule objectives.

5.6.1.7 Evaluation for Technology Development. Although MSO is a commercial process, its application to mixed waste treatment is very limited. Application of the process to mixed waste, including destruction rate efficiency, CO₂ generation, and dioxin and furan reformation, need further investigation.

5.6.2 Subsystem Technology Risks

The technology risks associated with the subsystems are substantially greater than in the baseline system due to lack of experience applying the MSO process to MLLW or any other similar wastes. Most of the relevant MSO data have been acquired only in bench-scale tests. Figures 2-33, 2-34, and 2-35 note components that are commercially available but require engineering development and demonstration on a system integration level.

5.6.2.1. Receiving and Preparation Subsystem. As discussed above, higher demands are placed on the sorting function of this subsystem than on the baseline system. This increases the complexity and size of the receiving and preparation subsystem.

5.6.2.2 Main Thermal Treatment Subsystem. The main thermal treatment subsystem in molten salt oxidation requires that large bulk items and noncombustible material be excluded from the feed stream. The optional feed stock for MSO is organic liquids with low ash content. Treatment by molten salt oxidation works best when the composition of the feedstock is consistent. However, because of the large heat sink available, gradual changes in the heating value of the waste feed are easily tolerated. The viscosity of the melt must be controlled to maintain effective oxidation of the waste. Ash and inert materials must be removed from the melt at a rate sufficient to keep the melt viscosity low. The fate of radionuclides in the melt should be assessed.

5.6.2.3. Primary Stabilization. There are no operating data to provide an estimate of the amount of carbon in the ash from the MSO process. Molten salt oxidation and vitrification tests are needed to determine the significance of carbon residue in the ash and to establish how effectively the carbon can be oxidized in the vitrification unit.

5.7 Evaluation of Molten Metal Waste Destruction (System G-1)

The molten metal waste destruction system employs a molten metal reactor. The melter operates at over 3000°F and operating pressures can be varied from slightly negative to highly positive. In this implementation, with the fluidized bed cooler in the APC system, positive pressure is required. An initial charge in the range of two to three thousand pounds of metal is fed to the reactor and melted to provide the heat source and the molten metal destruction bath. Additives such as lime and flux are fed to the reactor on demand, using nitrogen gas for delivery.

Incoming pumpable waste (liquid and sludge) is injected through the molten bath from inlets at the bottom of the reactor. Waste consisting of larger solids is fed from overhead hoppers through submerged inlet ports. The high thermal energy and catalytic effect of the molten metal dissociates the feed into its basic constituents, which dissolve into the metal. Once in this dissolved state, adding other reactants, such as fluxes and lime, enables elemental reformations and phase separation into gaseous, slag, and metal phases. Oxygen is added to the reactor at a substoichiometric rate to produce carbon monoxide and hydrogen in the offgas. Process byproducts consist of offgas, molten slag, and molten metal. Offgas flows to the APC subsystem. Excess metal is extracted from the process and cast into molds, with the potential for being recycled. Slag is tapped off into crucibles, allowed to cool, and then capped and sealed, resulting in a stabilized waste.

5.7.1 System Technology Risks

Overall, the risks of this system are judged higher than for the baseline system, based on the lack of commercial experience.

If its applicability to DOE MLLW can be established, there are a number of inherent advantages in using molten metal waste destruction when compared to the baseline case. The thermal destruction and primary stabilization in this system are performed in one step, thus reducing the need for

additional equipment, space, and material handling. Treated metal waste can be recycled within the DOE complex for use as containers and shielding for high-level radioactive wastes. The use of an electrically-heated molten metal bath as the heat source and a chemical reduction process to destroy organic material produces less offgas than the baseline system.

5.7.1.1 Regulatory Compliance. Permitting of the molten metal reactor for treating MLLW would be similar to permitting an incinerator, but it could be considered a non-flame thermal treatment process. The final waste form is a vitrified solid, which would meet LDR requirements. The potential for the recycling of the metals within DOE may reduce the disposal volume.

5.7.1.2 Environmental, Safety, and Health Objectives. Destruction removal efficiency is expected to meet regulatory standards, based on vendor testing. Due to extremely high reactor temperatures, organic compounds are broken down to their elemental forms. Consequently, no secondary combustion chamber is needed for destroying organic gases. However, this needs to be demonstrated and the DREs verified for DOE MLLW. The molten metal waste destruction is performed under reducing conditions, which are maintained by an excess of carbon in the metal bath. Oxygen, rather than air, is used as a combustion gas. The effect of using nitrogen as a carrier gas to transfer additives into the reactor needs to be assessed regarding the formation of nitrogen oxides. SO_x and dioxins should be significantly less than in the baseline case because of the reducing atmosphere. High solids emissions in the offgas (before offgas treatment) of as much as 20% of incoming solids are reported in one review of this process. This assertion is strongly disputed by one technology vendor, who reports that the recent designs restrict dust generation to less than 1 ng/Nm^3 . The offgas generated from the reactor is primarily hydrogen and carbon monoxide, which is easily converted to CO_2 and water in an energy recovery steam boiler or in a thermal oxidizer. The slag additives can be formulated to provide some acid gas scrubbing within the reactor, further reducing the size of the APC. The offgas volume from this system is less than that of the baseline system.

Experiments by the vendor indicate that from the metals partitioning standpoint, most of the radionuclides found in DOE MLLW may be categorized into four general groups: (1) uranium and transuranium, (2) technetium, (3) cesium and strontium, and (4) cobalt, nickel, and other isotopes with an atomic weight near iron. Vendor tests, using hafnium as a surrogate element, predict that the elements in the first group, uranium and transuranium, will most likely oxidize and go into the slag phase. This means that metal contaminated with these elements can be cleaned with a high decontamination factor, rendering the metal suitable for recycling. Developmental work performed by one vendor indicates that the elements in the second group could also be forced to partition into the slag phase. Furthermore, it is predicted that elements in the third group will be vaporized and enter the gaseous phase. Based on theoretical knowledge, elements in the fourth group are expected to prefer partitioning into the molten metal phase. Current knowledge about the special fluxes and catalyzers that control the fate of the isotopes in the molten bath is based on vendor tests. According to the vendor, experiments have produced durable, vitreous products with good incorporation of radionuclides into the ceramic or slag layer. Further development work is needed.

5.7.1.3 Evaluation for Treatment Effectiveness. The principal technology risks in molten metal waste destruction are due to melter design, removal of slag and molten metal, cooling, and packaging. All these operations take place at relatively high temperatures. Many delicate components and control instruments may be required to operate at such a high temperature. The applicability of this process to DOE MLLW is yet to be determined. Although some testing has been

performed, the effectiveness of the partitioning of radionuclides into the slag or metal layer must be assessed for a full-scale facility. A suitable and acceptable strategy for recycling must be developed. However, this process is potentially capable of significant volume reduction by providing organic destruction, inorganic material vitrification, and metal separation functions in one step.

5.7.1.4 Evaluation for Implementability. Development is needed for the reactor geometry, refractory, turbulence control, feed mechanism, instrumentation, and removal of slag and metal from the furnace. In addition, the behavior of radionuclides and volatile metals in the melter and the offgas treatment will require further testing, evaluation, and demonstration. In summary, a greater degree of uncertainty exists for this process than the baseline case, which could adversely impact schedule and cost. The mechanical availability of this system is not predictable due to lack of operational experience. The ability of the technology to go from bench scale to full scale also remains to be demonstrated. The nature of the metal produced and the additional processing that may be required to render the metal form suitable for recycling requires further evaluation. Assuming successful resolution of these issues, molten metal waste destruction's one-step processing could provide high flexibility and operability by consolidating operations.

5.7.1.5 Evaluation for Environmental, Health, and Safety Objectives. This is a one-step process, meaning that the amount of material handling during treatment is expected to be considerably reduced. There are some concerns raised in reviews of this process about the quantity of solids that are emitted and the ability of this process to provide adequate organic destruction without a secondary combustion chamber. The integrity of slag produced by molten metal waste destruction needs to be evaluated to determine if it meets DOE's requirements for stabilized waste. If metals produced by molten metal waste destruction are not recycled, their leachability must also be evaluated to identify if additional treatment is necessary. Personnel safety issues are of high concern because of the high-temperature processing and the pressurized metal bath. The potential for catastrophic accidents (e.g., hydrogen explosion) must be understood and evaluated. The process uses positive pressure; therefore, the confinement safety aspect of the system needs to be studied.

5.7.1.6 Evaluation for Stakeholder Concerns. The molten metal waste destruction process combines thermal treatment and waste stabilization in one treatment unit. The system vendor claims that this treatment is not considered incineration and will not require permitting as an incinerator. Total offgas produced is an order-of-magnitude below that produced by the baseline system. Both the offgas and the recovered metals are potentially recyclable. These features should increase the acceptance of this technology by the regulatory agencies and the public.

5.7.1.7 Evaluation for Life-Cycle Cost. Molten metal waste destruction is a developing technology. Therefore, accurate cost forecasting may not be possible. The FFCA guidelines note that systems that are not commercially developed have a higher possibility of cost overruns.

5.7.1.8 Evaluation for Technology Development. Molten metal waste destruction is an emerging technology, with no operating commercial units. According to the vendor, there are a number of molten metal waste destruction treatment facilities planned for treating nonradioactive waste, including a 30,000-ton per year molten metal waste destruction unit for hazardous waste scheduled for construction at a Rollins treatment, storage, and disposal (TSD) facility. Martin Marietta has announced that it will build a demonstration molten metal waste reactor at ORNL.

Experimental bases for separating radioactive components from the metal phase into slag have been developed. The large-scale applicability of this process to DOE's MLLW is yet to be demonstrated.

5.7.2 Subsystems Technology Risks

Figures 2-37 and 2-38 note components that are commercially available but require engineering development and demonstration on a system integration level.

5.7.2.1. Receiving and Preparation Subsystem. Compared with the baseline case, less extensive sorting is required because molten metal waste destruction can accept metallic, noncombustible, and combustible wastes. Size reduction requirements, however, are more extensive. For injection into the molten metal reactor, it is estimated that bulk solid materials must be reduced to 3 inches. Powdered solid feed through tuyeres is also possible. Sorting requirements will also be dependent upon regulatory waste characterization requirements.

5.7.2.2. Main Thermal Treatment Subsystem. There are a number of equipment and process issues that contribute to higher risks for this subsystem as compared to the baseline case. Some of the equipment issues that require further evaluation concern uncertainties with the responsiveness of molten metal waste destruction to changes in waste feed composition, molten metal removal, slag removal, and metal and slag casting and cooling. The feed mechanism approach and bulk waste feeding require development. The residence time for larger particles within the feeding system must be evaluated. Process issues that require evaluation include the ability of molten metal waste destruction to destroy organic materials without using a secondary combustion chamber and the leach resistance of the slag and molten metal. Control of particulates, radionuclides, toxic metals, and acid gases must be demonstrated for DOE MLLW.

5.8 Evaluation of Steam Gasification (System H-1)

The steam gasification system (System H-1) differs significantly from the baseline system. The main thermal treatment subsystem has an indirectly-fired organic gasification fluidized bed reactor operating at 1400°F. Superheated steam provides the oxidant and some of the heat for organic waste destruction. The use of indirect heating and a reducing atmosphere minimizes offgas generated. Only combustible waste is fed to the reactor; noncombustible debris and other solid materials are pretreated and fed directly to the vitrifier. Because of the need for sorting the combustible from noncombustible material in the feedstock, the receiving and preparation subsystem is more extensive.

5.8.1 System Technology Risks

Steam gasification is in an advanced state of development and has been used commercially for treating biomass waste, but overall this system is judged to have a greater technology risk than the baseline system when applied to MLLW. As with other gasification systems in this study, destruction effectiveness for a system that does not include secondary combustion is an area of concern. Another area of concern is the fate of radionuclides.

5.8.1.1 Regulatory Compliance. Steam gasification is a commercial process. The technology is expected to be permitted under industrial furnace regulations. The final waste form is a vitrified solid generated in the primary stabilization subsystem and should meet LDR requirements.

5.8.1.2 Evaluation for Environmental, Health and Safety. The efficiency of steam gasification in the destruction of organic compounds in the DOE's MLLW must be evaluated. Hydrogen gas, a product of organic gasification, must be handled to avoid explosions and other hazards. The potential for radionuclides to form volatile metals rather than nonvolatile oxides must be understood. (The metal form is more likely to volatilize than the oxide in the case of certain radionuclides.) Nitrogen oxides, dioxin, and furan formation are discouraged in a reducing atmosphere. The destruction removal efficiency for hazardous and MLLW should be demonstrated. The volume of wastes produced is somewhat reduced compared to the baseline system (Table 3-12).

5.8.1.3 Evaluation for Treatment Effectiveness. The system has not been used to treat DOE MLLW. The organic gasification process has a low tolerance for processing noncombustible waste and, therefore, treats only combustible waste, whereas the baseline system can treat both combustible and noncombustible waste. The waste must be reduced to particles less than 1/4 inch in size by tertiary shredding, increasing the mechanical complexity of the system. The particle size of the waste must be in a narrow range; particles must be small enough to be fluidized but large enough to remain in the reactor until the reaction is complete. Reactor temperature must be optimized; higher temperatures increase destruction removal efficiency but also contribute to slagging, which can plug the bed.

The separated, noncombustible material must be shredded and dried in a calciner to remove water vapor to provide a controllable feed to the vitrifier. The dryer offgas must be collected and, if necessary, routed to the APC. The dryer adds to the mechanical and control complexity of the system. Trace organic compounds and solids (e.g., plastics) in the noncombustible material could further complicate the dryer operations. Process control for the vitrifier operation could become difficult if organics are introduced into the unit. Incomplete combustion in the gasifier could result in a high-carbon ash, which might affect the quality of the vitrified product.

5.8.1.4 Evaluation for Implementability. Steam gasification has lower implementability than the baseline system. Because of prior application on biomass waste, design, construction, and operation would be expected to proceed on target. Successful operation is less certain. Availability will be negatively affected by the increased sorting, size reduction, and waste characterization requirements. The mechanical and process simplicity of the reactor combined with the commercial experience base will tend to improve availability and implementability.

5.8.1.5 Evaluation for Stakeholder Concerns. The volume of offgas discharged to the atmosphere is less than that of the baseline system (Table 3-11). Hydrogen gas produced during gasification can be used to generate steam or electricity, and the steam produced from the hydrogen can be recovered and recycled back to the gasifier. Production of nitrogen oxide byproducts, dioxins, and furans is lower due to operation in the reducing mode. The process operates at a lower temperature compared to the baseline process and does not involve incineration. These aspects of the technology may result in better acceptance of the thermal treatment facility by the public and the state and regulatory agencies.

5.8.1.6 Evaluation for Life-Cycle Cost. Because steam gasification is a commercial process, costs are understood. Costs for radioactive containment and waste stabilization add to the life-cycle cost. Cost and schedule targets should be achievable.

5.8.1.7 Evaluation for Technology Development. This technology has potential for operations within and without the DOE complex. Some development of this technology with MLLW will be necessary to assess operating and design parameters. Steam gasification work to date has focused on biomass gasification, energy recovery, and sludge gasification. Development for DOE MLLW streams is still needed.

5.8.2 Subsystems Technology Risks

The technology risks associated with the subsystems are greater than those for the baseline system. Figures 2-40, 2-41, and 2-42 note components that are commercially available but require engineering development and demonstration on a system integration level.

5.8.2.1. Receiving and Preparation Subsystem. Higher demands are placed on the sorting function of this subsystem than that of the baseline system. This increases the complexity and size of the receiving and preparation subsystem.

5.8.2.2. Main Thermal Treatment Subsystem. The main thermal treatment subsystem represents technology that is in an advanced stage of development. Some commercial applications to hazardous sludge from paper mills and biomass waste exist. There is no experience with radioactive mixed waste. The process requires that large bulk items and noncombustible material be excluded from the feed stream. Steam gasification performs best when the composition of the feedstock is consistent, although gradual changes in the heating value of the waste feed are easily tolerated. Features to control oxygen concentration and maintain pyrolysis conditions in the fluidized bed gasifier must be incorporated. The pyrolyzer requires an evenly mixed and well-distributed underfire air flow to minimize carbon in the ash. Operating conditions must be maintained to avoid plugging the bed with slag. The destruction efficiency of low-temperature pyrolysis must be investigated further.

5.8.2.3. Primary Stabilization. Incomplete combustion in the steam gasifier could result in carbon in the ash, which complicates vitrification chemistry and affects the leachability of vitrified waste. Steam gasification and vitrification tests are needed to determine the quantity of carbon in the ash and to establish how effectively the carbon can be oxidized or encapsulated in the vitrification unit.

5.9 Evaluation of Joule-Heated Vitrification (System J-1)

The joule-heated vitrification process has been used to treat radioactive and MLLW. This system satisfies two process objectives: vitrification of noncombustible waste, and oxidization of the combustible waste. The main thermal treatment subsystem has an electrically-heated melter unit, head space for organic oxidation, and operates at 2700 to 3000°F. In System J-1, the need for a primary stabilization subsystem is eliminated, since thermal treatment and primary stabilization (vitrification) are combined in one subsystem.

5.9.1 System Technology Risks

The system has greater technology risks than the baseline system. Some of the risks associated with joule-heated vitrification are discussed below.

5.9.1.1 Regulatory Compliance. Permitting of the Joule melter would be similar to permitting of an incinerator, but it could be considered as a non-flame thermal treatment process. One vitrification system design is undergoing permitting as a thermal treatment process for commercial use in Tennessee and Washington. Tests that provide information on the technology's effectiveness in producing a leach-resistant slag from the DOE's MLLW stream are needed.

5.9.1.2 Evaluation for Environmental, Health and Safety. Currently, tests of this technology are being performed on the DOE's MLLW to assess emissions. The inclusion of a secondary combustion unit should yield the required destruction removal efficiency. The rate of particulate emissions and the fate of radioactive metals must be evaluated. The volume of emissions produced in the Joule melter is less than 1/3 of the volume of the baseline system. This system reduces worker exposure relative to the baseline system due to the elimination of the need for a separate vitrification unit.

5.9.1.3 Evaluation for Treatment Effectiveness. Joule-heated vitrification can process both combustible and noncombustible waste. The effectiveness of the melter in the treatment of combustible waste must be assessed. Processing at high temperatures is required to meet objectives of both organic destruction and inorganic stabilization.

One vendor stated that the Joule melter could be adapted for either an oxidizing or a reducing atmosphere. A reducing atmosphere would produce a syngas of hydrogen and carbon monoxide. The processing atmosphere is dependent on the level of organics in the feed as well as the addition of oxidants.

The presence of metals and organics with high carbon content in the waste feed can cause short circuiting of the electrical cell in the reactor and reactor vessel degradation. Short circuiting occurs when metal oxides are reduced to the elemental metal form, settle to the bottom of the reactor, and cause short circuiting. Nonuniform glass formation results from short circuiting. To alleviate this problem, an oxygen lance can be installed on top of the melt to eliminate reduction of the metal oxides. One vendor states that reactor design modifications can avoid short circuiting. Key features in this design are 1) the use of a cold-wall of solidified, self-healing glass rather than refractory to provide a thermal barrier, 2) vertical electrodes positioned remotely, and 3) separate bottom drains for metals and glass removal to avoid accumulation of liquid metals on the bottom of the reactor. This system also allows the metal to be removed and cast into ingots.

Since noncombustible material is fed directly to the vitrifier, the waste must be shredded and dried in a calciner to remove water vapor. The dryer adds to the mechanical and control complexity of the system. In other designs drying is not required for waste that is less than 20% moisture.

5.9.1.4 Evaluation for Implementability. Lower temperature joule-heated melters are a commercial technology in the glass industry. Problems are not anticipated in the design and construction of the melter. Operability is less certain. Electrode lifetime could be limiting in the

high-temperature application, resulting in downtime for replacement. The limited feedstock sorting of this system will increase availability. However, more feed sorting will be required than in other one-step processes such as the slagging kiln and plasma vitrification. Metals content is limited to 20% of the feed, according to vendor. Metal drums cannot be fed to the melter.

Because of lack of experience with the DOE's MLLW and waste processing in general, the availability of the equipment is not predictable. Scale-up of this process from bench-scale tests to full-scale operation has not been demonstrated. A commercial unit that is scheduled to begin construction in 1995 will provide information on the use of this technology for waste treatment.

5.9.1.5 Evaluation for Stakeholder Concerns. The joule-heated melter combines thermal treatment and waste stabilization in one treatment unit. Although it is a high-temperature thermal process, it is expected that open flame in the head space during an oxidation condition will be limited. If operated to produce syngas, recyclable gases could be generated. The simplicity of this joule-heated melter approach may increase acceptance of the thermal treatment facility by the public, the state, and regulatory agencies.

5.9.1.6 Evaluation for Life-Cycle Cost. Capital costs can be assembled with accuracy, but there is a greater degree of uncertainty with operational and maintenance costs due to lack of commercial experience.

5.9.1.7 Evaluation for Technology Development. Although the Joule melter has been developed for waste processing, it cannot at this time be considered a commercial process. Bench-scale studies have been performed using surrogate radioactive waste, but full-scale testing remains to be performed. The flexibility of the system to allow processing the variety of waste types in DOE's MLLW has not been demonstrated.

5.9.2 Subsystem Technology Risks

The key issues of concern for the main thermal treatment subsystem are the fate of radioactive metals in the vitrifier and the leachability of the slag and metal solids produced. Appropriate feed characterization, additives, and operational control are necessary to produce an acceptable final waste form. The ability of the technology to accept process feed variations and to avoid process upsets must be understood.

Most experience with Joule melter systems operating at about 1050 to 1100°C is with relatively constant composition feed streams such as the DOE high-level waste liquids. Glass systems, such as the borosilicate system, have fairly narrow compositional ranges for good leach resistance. For the MLLW application, feed chemistry will vary widely and the ability to form a good glass without increasing the additive to residue loading ratio used in this study is questionable (1 part additive to 2 parts inorganic residue or waste). Mass ratios of 1 to 1 or greater have been required to obtain satisfactory leach rates in tests performed at Savannah River Laboratory. Additional waste sorting will be required to remove metals from the feed stream. In general, Joule melters will not operate with more than a minor metal content, due to shorting of the electrodes.

The subsystem technology risk of the APC is very similar to that of the baseline system, because both treat offgas from a high-temperature, oxidizing atmosphere process.

Technology risks associated with the other subsystems are the same as in the baseline system. Figures 2-44 and 2-45 list components that are commercially available but require engineering development and demonstration on a system integration level.

5.10 Evaluation of Thermal Desorption and Mediated Electrochemical Oxidation (System K-1)

The main objective of this thermal desorption (TD) and mediated electrochemical oxidation (MEO) system is to use innovative low-temperature technologies as an alternative to high-temperature incineration for the volatile organic waste fraction. The TD system would take advantage of the EPA's debris rule for hazardous waste processing that allows minimal processing and stabilization of a certain category of MLLW debris (trash-like material). System K-1 is characterized by low-temperature processing and by its perception as a nonincineration technology. The system uses a main thermal treatment process, TD, combined with an organic liquid waste process, MEO. (MEO is not an appropriate technology for treating solid waste streams and was, therefore, combined with other technologies to create a total treatment approach.) Solids are treated in the thermal desorption system, while organic liquid is sent directly to the MEO system. Condensed offgas from the desorber is also sent to MEO. Solids leaving the desorber are grouted in the primary stabilization subsystem.

This system is very different from the baseline system. The indirectly-heated thermal desorber treats combustible and noncombustible waste, with the organic liquids in the offgas being condensed and treated by MEO. MEO converts the liquid organic waste into primarily carbon dioxide and hydrogen, which is readily converted to water in a thermal oxidizer. The use of grouting avoids high-temperature thermal treatment and takes advantage of the EPA debris rule. However, the use of grouting for process residues (e.g., sludges) must be reviewed to assure that the waste will meet the EPA TCLP test criteria. The EPA debris rule precludes grouting of process waste such as sludge. Combustible waste sent to the desorber must not include process waste.

5.10.1 System Technology Risks

The system has a much higher technology risk than the baseline system. The main thermal treatment and APC subsystems using thermal desorption are less complex than the baseline main thermal treatment and APC subsystems, but there is very little experience with the approach used by this system and that only on a small scale. The primary stabilization subsystem must accommodate both noncombustible and combustible solid waste residues from thermal desorption. The final waste volume will be higher than in the baseline system, and with grout stabilization, the waste form will be less stable.

5.10.1.1 Regulatory Compliance. Thermal desorption is a commercial, accepted approach that has been permitted for hazardous waste treatment, usually contaminated soils. MEO would be permitted as an aqueous treatment method, which is simpler than permitting an incinerator. Grouting produces a less stabilized waste form and a larger volume than does the baseline system. The waste form developed from the grout stabilization should be evaluated for acceptability under regulatory standards (EPA and DOE). Process control will be complicated due to waste variability and more waste characterization may be required. Permitting of this system may not be possible. It would have to be demonstrated that TD and grouting are an adequate treatment for process waste.

5.10.1.2 Evaluation for Environmental, Health and Safety. This system will produce emissions from two areas: the main thermal treatment thermal desorber APC and the MEO process. The MEO process produces an H₂ offgas stream that could include some volatile organics. MEO also generates a separate offgas stream containing carbon dioxide and chlorine. The chlorine is removed in a scrubber. The remaining offgas from these two streams is directed to a thermal oxidizer. Thermal oxidation is a well-understood process and should be effective for treating these streams.

5.10.1.3 Evaluation for Treatment Effectiveness. The effectiveness of the thermal desorber in volatilizing the combustible waste fraction has not been determined. The desorber must operate in a low oxygen environment. The combustible waste could generate noncondensable combustion products, which must then be sent to thermal oxidation.

A key operating concern for the system is the strategy of processing waste containing plastic material in a desorber unit. Unless operating temperatures are kept very low, the plastic will have a tendency to melt in the desorber and stick to the internal desorber surfaces. It is also possible that the unit will be plugged by large pieces of agglomerated solids formed in the desorber. At low operating temperatures, the ability of a thermal desorption process to remove organic material is limited.

The fate of mercury in the thermal desorber must be evaluated. Typical operating temperatures are below the boiling point of mercury, indicating that most mercury will remain with the solid waste and be transferred to primary stabilization. The APC includes a heat exchanger to lower the temperature of the offgas to a temperature sufficient to collect vaporized mercury, in the event that thermal desorption conditions generate it. The removal of vaporized mercury via this primary condenser or heat exchanger needs development. The design specifies that mercury be separated from the offgas before condensing water and other vapors.

The treatment effectiveness of MEO has been demonstrated on the bench scale in tests at LLNL and PNL. The full-scale operating parameters remain to be developed.

5.10.1.4 Evaluation for Implementability. Sorting requirements for this system are extremely high. The availability of the thermal desorption equipment could be affected by processing plastics and combustibles. MEO is a young technology for the processing of MLLW. Scale-up of this process involves adding more electrochemical cells and should be predictable. Lack of operating data limits the ability to forecast effectively. Implementability risks are high.

5.10.1.5 Evaluation for Stakeholder Concerns. The volume of final waste requiring disposal is greater than that of the baseline system. Less offgas will be discharged from the main thermal treatment subsystem. Total offgas discharged from the thermal treatment, MEO, and primary stabilization systems will be a fraction of that discharged by the baseline system (Table 3-11). Since the system consists of nonincineration processes, better public and regulatory agency acceptance is possible if destruction efficiency is demonstrated.

5.10.1.6 Evaluation for Life-Cycle Cost. The development of MEO technology could affect the schedule objectives for this project. Cost estimates for an emerging technology cannot be dependably forecast. The cost of disposal of grouted waste adversely affects the overall cost of System K-1.

5.10.1.7 Evaluation for Technology Development. Thermal desorption is a commercial technology for the processing of hazardous waste, especially contaminated soil. Adapting this technology to the processing of the DOE's MLLW requires further development.

The MEO technology cannot be considered commercial yet. A number of prototype organic destruction systems using commercial electrochemical cells have been built. The technology is being developed in conjunction with work being performed at Lawrence Livermore National Laboratory. The relative simplicity of the individual process components suggests that the process can be commercialized when the operating parameters are fully understood.

5.10.2 Subsystem Technology Risks

Figures 2-47 and 2-48 note components that are commercially available but require engineering development and demonstration on a system integration level.

5.10.2.1. Main Thermal Treatment Subsystem. The thermal desorber results in much higher technology risks for the main thermal treatment subsystem than in the baseline system. Key areas of uncertainty are the effectiveness of volatilization of organics in the desorber and the end state of combustible waste after passing through the desorber. Wastes such as sludge, paper, cloth, and cardboard might burn incompletely, generating organic compounds such as methane that are not condensable. The solid wastes from the desorber are grouted, and noncondensable organics are combusted by thermal oxidation. The operating temperature of the desorber must be studied further. The volatilization and combustion of the DOE's MLLWs in the desorber should be investigated. Ways to avoid or accommodate plastic melting and incomplete combustion of paper and low-temperature-burning compounds in the desorber while still getting effective organic desorption must be developed.

The operating temperature of the thermal desorber is a key parameter for successful treatment of the waste. Table 5-2 lists the RCRA contaminants typically present in the DOE's MLLW with their boiling points and freezing points. At about 540°F, polyvinyl chloride (PVC) starts releasing chlorine gas, and at 900 to 1,300°F complete pyrolysis takes place. Since PVC or other, similar, plastics are present in the feed, the desorber should operate at a temperature below 540°F. Considering the boiling points of the organic compounds (Table 5-2), they will all be volatilized at a temperature of about 300°F, except PCBs. (Xylene has the highest boiling point, 281°F.) It is, therefore, possible to operate the desorber at 300 to 400°F and preserve the integrity of PVC compounds while desorbing the volatile organics.

PCBs behave differently than the other organic compounds in the feed. PCBs typically boil at 680 to 740°F. PCB-contaminated waste will have to be separated from plastic waste and batched through the desorber at about 800°F. In the event that PCBs and high-boiling-point organic wastes such as pesticides are sent through the desorber at lower temperatures, these wastes will be transferred to the grout primary stabilization. No destruction occurs in primary stabilization. If grouted waste does not pass TCLP tests, it will require rework.

Mercury boils at 674°F and will, therefore, not be recoverable from the desorber unless it is processed by itself at temperatures above 700°F or with PCB waste. The other RCRA metals listed

(Table 5-2) have boiling points higher than the temperatures reached in the desorber. Figure 5-1 shows these different operating modes of the desorber for treating the various types of feed.

Both combustible and noncombustible solid waste is sent to the thermal desorber. The volume of treated waste is much larger than that of the baseline system, where combustibles undergo an 85-90% volume reduction in the incinerator. Desorbed waste is stabilized by grouting, which produces a final waste form about three times more voluminous than that of the baseline system.

5.10.2.2. Liquid Organic Waste Treatment. The MEO subsystem also results in higher technology risks. MEO treats organic liquids from the desorber or from the receiving and preparation subsystem. Organic liquids are about 3% of the total waste feed. The ability of the MEO cells to handle feed variations must be assessed. The frequency of electrolyte replacement and potential for regeneration of the electrolyte must be developed. The vendor is working to apply commercially-available equipment to electrolyte recycling but the process is not currently available.

5.10.2.3. Primary Stabilization. The primary stabilization subsystem has greater technology risks than that of the baseline system. The volume of solid waste and offgas will be greater because more waste will be processed in this subsystem. The final grouted waste form is less stable than a vitrified waste. Process residues cannot be treated by this approach and should not be sent to the thermal desorber. The waste feed must be evaluated to remove process residue waste. Process residue would be solidified with polymer to achieve the desired leachability. Additionally, nonvolatilized organics remaining in the desorbed solids will not be destroyed. These organics and mercury will have the potential to leach from the grouted waste. The use of grouting as a stabilization technology is a higher risk approach than vitrification. Disposal costs of grouted waste are much higher than those of the baseline system due to the larger volume.

5.11 Evaluation of Thermal Desorption and Supercritical Water Oxidation (System L-1)

This system uses a main thermal treatment process combined with a liquid organic waste treatment process: thermal desorption and supercritical water oxidation. Solids are treated in the thermal desorption system, while organic liquids are sent directly to the SCWO system. Condensed offgas from the desorber is also sent to SCWO. The description and evaluation of the thermal desorption and primary stabilization processes are the same as that presented for System K-1 (Section 5.9) and are not repeated here.

Organic liquid waste, such as sludges and liquified waste, is treated by SCWO. Solid waste could be finely ground and then liquified as feed preparation to SCWO. To avoid the extensive feed preparation required to liquefy solid waste streams, thermal desorption and gas condensation were combined to provide an aqueous feed to SCWO. The option of inputting the gases from the thermal desorber directly to SCWO was not included in this study. Controlling and compressing hot gases to the high pressures of SCWO would add to the process and mechanical complexity of the system and increase risks to workers. SCWO converts its input liquid feed into carbon dioxide, water, and inorganic salts. The types of salts depend on the chemical constituents in the waste feed.

5.11.1 System Technology Risks

The overall system has a much higher technology risk than the baseline system. Thermal desorption risks are discussed in Section 5.8.1.

5.11.1.1 Regulatory Compliance. Thermal desorption is a commercial, accepted approach that has been permitted for hazardous waste treatment, usually contaminated soils. SCWO would be permitted as aqueous treatment method, which is simpler than permitting an incinerator. Grouting produces a less stabilized waste form and a larger volume than does the baseline system. The waste form developed from the grout stabilization should be evaluated for acceptability under regulatory standards (EPA and DOE).

5.11.1.2 Evaluation for Environmental, Health and Safety. This system will produce emissions from two areas: the main thermal treatment thermal desorber APC and the SCWO process. The offgas from the thermal desorber is treated by thermal oxidization. The SCWO process produces an offgas stream that is treated by particulate and carbon filtration. One of the major advantages of SCWO is that it requires minimal APC equipment. The destruction removal efficiency of organics from the SCWO process has been demonstrated to be above regulatory limits for numerous organics. Safety is a major issue, due to the high operating pressures.

5.11.1.3 Evaluation for Treatment Effectiveness. The effectiveness of the thermal desorption is the same as discussed in Section 5.9.1.3. The SCWO unit has the potential to completely destroy all organic wastes; however, the system is unproven for the DOE's MLLWs. In addition, the system uses very high pressure which creates extra maintenance costs. SCWO can treat liquid organic waste and sludge that can be transferred to the reactor. This represents about 3% of DOE's total MLLW.

5.11.1.4 Evaluation for Implementability. SCWO is an emerging technology. Design and operational issues regarding salt build-up, reactor corrosion, and high pressure operation remain to be fully resolved. Alternative materials and engineering approaches are being developed to reduce the corrosion that occurs in the transition zones from subcritical to supercritical temperatures. One vendor recommends the use of a tubular reactor to ease the removal of salts. Scale-up of the high-pressure process remains to be demonstrated. SCWO is presently operated on liquid feedstreams with minimal inert materials. Unresolved operational issues indicate availability may be negatively affected.

5.11.1.5 Evaluation for Stakeholder Concerns. The volume of the final waste requiring disposal is greater and the waste form is less stable than for the baseline system. The public and state and local agencies will view these aspect of the L-1 system less favorably than those of the baseline system. In its favor, this system does not incinerate the waste and, therefore, cannot have products of incomplete combustion. It discharges less than 15% of the offgas to the atmosphere that the baseline system discharges. Since thermal desorption and SCWO are not classified as incineration technologies, the system will probably be more acceptable to the public, and state and local agencies, provided data are available demonstrating suitable destruction efficiency.

5.11.1.6 Evaluation for Life-Cycle Cost. SCWO is an emerging technology. Cost and schedule cannot be forecast accurately at this stage of development.

5.11.1.7 Evaluation for Technology Development. SCWO has potential for destruction of organic compounds in liquid waste streams. Eight private firms are developing the process and there are potential markets within and outside DOE. One full-scale plant is presently destroying liquid organics at five gallons per minute. Pilot plants are presently operating on a variety of liquid organic feeds.

5.11.2 Subsystems Technology Risks

Figures 2-50 and 2-51 note components that are commercially available but require engineering development and demonstration on a system integration level.

5.11.2.1 Main Thermal Treatment. The thermal desorber subsystem evaluation is the same as that discussed under System K-1, Section 5.9.2.

5.11.2.2 Liquid Organic Waste Treatment. SCWO is an innovative, new technology. The first commercial SCWO plant began operating in spring of 1994 in Austin, Texas. This facility processes a petroleum-based liquid stream. The technology remains largely untested on the DOE's MLLW streams.

The process operates at a temperature of about 1000°F and a pressure above 22 MPa (230 atmospheres), which creates safety and maintenance challenges. In addition, the production of inorganic salts inside the reactor vessel creates potential corrosion problems. These corrosion problems are exacerbated by the high operating pressures. Significant problems with chloride-assisted stress corrosion cracking should be expected.

Operation of the pilot plants has been hampered by clogging of valves and lines with inorganic salts precipitating out of the supercritical water. Various reactor designs have been developed to minimize clogging and to provide approaches to salt management and removal. Control of salts is critical to minimize equipment maintenance.

The pressure reduction from the SCWO reactor and separation of gas, liquid, and solid must be optimized. The evaporative wipe filter technology must demonstrate its ability to treat the DOE's MLLW. It has to be shown to be effective in removing concentrated salts from the liquid.

The SCWO process can treat only liquid and low-viscosity sludges that are pumpable. Concentrated organic waste might have to be diluted before treatment, increasing the volume of fluid to be handled.

5.11.2.3 Primary Stabilization. The primary stabilization subsystem has greater technology risks than that in the baseline system as discussed in Section 5.8.2.

Table 5-1. FFCA Treatment Selection Ranking Guide

Number	Treatment Selection Guides	High Score	Middle Score	Low Score
1. REGULATORY COMPLIANCE				
1a	Regulatory Compliance	All process-related regulations are met through standard processes	Most regulations are met, with the balance possibly being met through requests for variance	Majority of regulations cannot be met without variances or other extensive measures
2. ENVIRONMENTAL, HEALTH AND SAFETY				
2a	Environment/Public Health	Little or no facility emissions for routine operations or under all but the most catastrophic accidents	Little or no facility emissions for routine operations but significant releases under most accident scenarios	Marginally acceptable releases under routine operations and/or extensive releases under most accident scenarios
2b	Non-Operational Worker Health and Safety	Significantly less number of workers required to construct and decommission a facility with the proposed process, as compared to other technologies, plus lower than average non-routine maintenance required	Average number of workers and nonroutine maintenance required	More complex than average facility construction, non-routine maintenance and decommissioning
2c	Operational Worker Health and Safety	Significantly fewer workers potentially exposed or potential exposure much lower than average	Average number of workers and potential exposure levels	Greater than average number of workers required or greater than average potential exposure to the work force
2d	Transportation Risk	No transportation of treated or untreated waste required	Limited additional characterization required to support transportation, no new packaging /certification facilities required, and limited number of waste transports required	Significant additional waste characterization required for transportation, new packaging/certification facilities required, large number of waste transports needed, or large number of miles required for each waste shipment

Table 5-1. Continued.

Number	Treatment Selection Guides	High Score	Middle Score	Low Score
3. TREATMENT EFFECTIVENESS				
3a	Volume Reduction	Factor of 5 reduction in volume of waste	Volume is maintained at 1:1 after processing	Volume is increased by a factor of 2 or greater
3b	Secondary Waste Generation	Secondary waste is easily treated using existing technologies	Treatment of secondary waste requires modification of existing technologies	Secondary waste has no known technology for treatment
3c	Destruction, Removal, & Demobilization Efficiency	All of the applicable LDR standards are met	Additional LDR treatment is required for some of the constituents and technology exists	Additional treatment is required to meet requirements & technology does not exist or requires modification
3d	Flexibility	Minimal system inefficiencies are experienced for off-design input	Off-design inputs are acceptable but cause reduced efficiency	Special precautions must be taken to avoid off-design input
3e	Final Waste Form	Meets the expected disposal WAC	Residues require additional treatment to meet disposal WAC and technologies exist	Significant additional treatment is required prior to disposal and/or technology does not exist
3f	Ability to be Shipped	Treatment residuals meet shipping requirements without any additional treatment	Treatment residuals only require simple physical treatment to meet shipping requirements	Treatment residuals require extensive treatment to meet shipping requirements
4. IMPLEMENTABILITY				
4a	System Implementability	Most of the elements and process previously demonstrated	50% or less of the elements have been previously demonstrated	Few or no elements have been demonstrated

Table 5-1. Continued.

Number	Treatment Selection Guides	High Score	Middle Score	Low Score
4b	Availability	Facility or system exhibits superior reliability and is available with minimal downtime	Process is expected to be available 50% of the time	Process is expected to be available less than 20% of the time
4c	Schedule for Waste Treatment	Waste can be processed within short time frame, schedule allows for some slippage	Waste can be processed within required time frame but allows for no slippage	Critical path approaches or exceeds milestones for designated waste
5. STAKEHOLDER CONCERNS				
5a	Public Acceptance	Stakeholders accept the process and risks	Some stakeholder concerns that could affect the successful utilization of the technology	Significant stakeholder concerns about process
6. LIFE-CYCLE COST				
6a	Life-Cycle Cost	Life-cycle costs can be supported within target budget	Life-cycle costs can be supported with less than 10% increase in target funding level	Line item funding required at high levels
7. TECHNOLOGY DEVELOPMENT				
7a.	Market for Technology	Numerous markets are identified within and outside DOE	More than one market is identified within and outside DOE	No markets or needs are identified

Table 5-2. RCRA contaminants included in the INEL waste characterization.

Contaminant	Boiling Point (°F)	Freezing Point (°F)
1,1,1-trichloroethane	237	-34
Carbon tetrachloride	170	-9
1,1,2-trichloro-1,2,2-trifluoroethane	118	-31
Trichloroethene	189	-99
Perchloroethylene	250	-2
Methylene chloride	104	-139
Methyl alcohol	147	-144
Butyl alcohol	243	-129
Xylene	281	-56
PCBs	689-734	50
Nitric acid	181	-44
Mercury	674	-38
Lithium	—	-38
Beryllium	4,532	2,349
Cadmium	1,409	610
Lead	3,164	621

6. DEMONSTRATION, TESTING, AND EVALUATION NEEDS

This section identifies the minimum demonstration, testing, and evaluation (hereafter referred to as development) necessary to resolve technical uncertainties associated with the technologies evaluated in this study. Identification of the development needs does not constitute endorsement of the technology nor does it constitute a recommendation to fund the development activities. It simply represents the views of the authors as to key development needs or technical data voids that should be resolved prior to full-scale implementation of the technology. This section is intentionally limited to the highlights or top level technical needs—it is not intended to provide a technology development plan for each system.

The section is organized to first describe development needs common to all systems, and secondly describe development needs for individual systems.

6.1 Program Mission and Objectives

Before the development program is launched, the mission and objectives must be defined. A suggested mission and objectives statement is presented below. This statement is suggested based on the ITTS study; it has not yet been adopted by DOE. DOE's formal adoption of a statement will require detailed review.

6.1.1 Mission

The mission of the program is to conduct a prototype demonstration of an integrated thermal treatment system for management of MLLW currently being stored or generated throughout the DOE Complex. The size of the demonstration system shall be large enough (about 100-300 lbs/hr) to provide reliable data for scale up. The program should encompass demonstration units and associated bench-scale test and evaluation activities, all executed to achieve the program goals and objectives.

6.1.2 Objectives

The objective of the program is to provide the technical basis for design of a production-scale integrated thermal treatment system for managing DOE's MLLW. This includes selecting the main thermal treatment unit, APC, and the associated support systems. The production-scale facility, which the demonstration program represents, must (1) meet current and future regulatory criteria, (2) minimize public and worker health risks by minimizing releases to the environment, (3) produce a waste form that ensures long-term isolation from human contact once it is in a MLLW land disposal unit, and (4) optimize cost.

The demonstration program must (1) examine the latest state-of-the art technologies, (2) conduct necessary bench-scale tests and treatability studies, (3) select one or more technologies for prototype demonstration, and (4) provide all information needed for detailed design of the production facility, which will begin in FY 1996.

6.2 Suggested Program For Common Development Needs

The development program consists of initial evaluation of technological options, conducting bench-scale tests, and selecting one or more parallel units for prototype demonstration. A facility (existing or new) will be provided to house the demonstration unit(s). The demonstration unit will be designed, fabricated, installed, and operated for a minimum of one year. At the end of this period,

key design features of the production-scale facility will be defined and finalized. The demonstration facility may continue operation beyond the initial first year if it can help refine the design of the production facility.

The program will bring all current thermal treatment research and development (R&D) and demonstration efforts under one umbrella. Accordingly, the program will be divided into the components discussed below. In addition to these components, the program will be integrated by a system integration group.

6.2.1 Incinerator Demonstration

Typical tasks assigned to this component would include the following:

- Treatability studies using bench-scale systems.
- Optimizing operation of incineration units (rotary kiln parallel with another technology) by treating surrogate waste.
- Preparing a detailed cost/benefit analysis for using oxygen in thermal treatment systems.
- Developing improved solids-handling systems for both feed to and discharge from the thermal treatment system.
- Developing improved air exclusion systems for the incineration subsystem.
- Running field tests to determine the correctness of volatility prediction techniques.
- Testing of ash slagging, and defining process parameters to prevent ash slagging.

6.2.1.1 Incineration Task Force. An Incineration Task Force should be established to address the problems associated with thermal methods of waste destruction. This task force should be made up of personnel from various DOE facilities, the EPA, and possibly the DOD.

6.2.1.2 Establish An Incineration Test Facility. The program should establish an incineration test facility from among the numerous incineration installations already in the DOE complex. With this facility, various matters affecting the public's concern about incineration of hazardous and mixed waste could be tested and evaluated. While the proposed plan is for a single facility, it is conceivable that the program may want to add support to ongoing projects at a number of sites.

6.2.1.3 Test Improved Rotary Kiln Seals. The biggest drawback in using rotary kilns for destruction of hazardous wastes has been the leakage of seals. Testing is needed to develop and prove the efficacy of advanced seal concepts to allay public and regulator fears. The status of seal development needs to be assessed to determine if advanced graphite/steel seals are adequate, or if alternatives such as magnetic fluid seals should be developed and tested. The kiln seal studies being conducted at the Savannah River Site on graphite face seals should be accelerated. A survey of U.S. and European rotary kiln seal performance/development should be conducted. A focused Request for Proposals issued by the task force would call for incinerator system vendors to demonstrate innovative seal performance. These studies should be performed over a wide temperature range to include both ashing and slagging kilns.

6.2.1.4 Characterize Fly Ash And Bottom Ash. The Incinerator Task Force should implement program activities designed to characterize the bottom ash and fly ash produced by various units around the DOE complex. This would aid in specifying the APC subsystem and characterizing the feed to vitrification and polymerization stabilization steps.

6.2.1.5 Quantify Partition Factors For Volatile Components Of The Waste. This task would permit the program to gain a better understanding of testing already done by others. At the same time, the Incineration Task Force could initiate research and development work in physical chemistry and chemical engineering to establish the thermodynamic basis for the behavior of volatile inorganic compounds generated during incineration and other thermal treatment processes. In general, these materials are chlorides and fluorides. The evaluation should include a wide temperature range (1400 to 3100°F) and both oxidizing and reducing conditions. This task could work to optimize conditions that favor retention of volatile metals and salts in ash during combustion and vitrification.

Particular attention should be paid to the carryover of mercury in the incineration and vitrification offgas. Potential additives for pyrochemical reduction of Hg^{+2} to Hg metal within the incinerator should be identified. Research into anaerobic thermal desorption for removing mercury and VOCs from combustible waste is recommended. Such a unit should have a temperature range capable of desorbing mercury metal and its sublimable sulfide and chloride salts. The relative merits of nitrogen, CO_2 , and superheated steam as an inert gas/heat transfer agent for such a system should be evaluated.

6.2.2 APC Demonstration

This component will encompass development of APC parts that satisfy regulatory and system requirements. Typical tasks of this component would include the following:

- Defining the analytical requirements for the system.
- Defining mercury removal and pre-HEPA filter designs and testing them in a demonstration-scale system.
- Optimizing the system design to minimize formation of dioxin and release of metals and products of incomplete combustion (PICs).
- Performing bench-scale studies of delayed CO_2 release systems and assessing the feasibility of this concept.

6.2.2.1 Air Pollution Control Systems Task Force. A multi-site Air Pollution Control Systems Task Force should be established to show that offgas from the various subsystems will be satisfactory for discharge to the atmosphere.

6.2.2.2 Removal Of Volatilized Mercury And Its Salts From The Offgas Stream. How to remove mercury from the offgas stream and how to dispose of it are equally important questions to be answered by the program. Laboratory and thermodynamic modeling studies should be conducted to predict the types and quantities of mercury species expected to form from incineration of mercury-containing wastes. It should be assumed that mercury is not removed prior to incineration, that it is present in several forms when leaving the incineration subsystem, and that it has the potential to distribute itself throughout all segments of the APC subsystem of the ITTS. The APC subsystem

should be developed to address all these aspects of mercury behavior. Technologies based on using impregnated carbon or alkaline scrubbing solutions to remove mercury from offgas deserve development focus. Efficient mercury removal subsystems capable of high loading at elevated temperatures should be developed.

In the APC subsystem, mercury can probably be removed from the offgas using fixed beds of sulfur-impregnated activated carbon. Nucon International, Inc., sells this technology under the name Mersorb. One of the principal drawbacks of this technology, from the standpoint of ITTS, is that the treatment must be carried out at temperatures of 100°C or less to prevent oxidation of the sulfur with an oxygen-containing offgas. In addition, the relative humidity must be maintained below 90% to prevent condensation of moisture in the carbon. Offgas treated in this manner would have to be reheated before discharge to prevent plume formation. Brna and others¹ fed powdered activated carbon and lime into offgas produced by a municipal waste combustor. They found that the carbon feed rate was the principal controlling factor and that it was directly proportional to mercury removal efficiency. They also determined that the source of carbon (coal, wood, or lignite), the location at which the carbon was added, addition of ammonia (to control nitrogen oxides), and variations in temperature (over the limited range) had little or no effect on mercury removal. The effect of lime addition was inconclusive. Lerner² explained that an alkaline scrubber solution must contain an oxidizer (peroxide or hypochlorite) or must be maintained at a (relatively) low pH for the solution to effectively remove mercury from offgas. Beco Engineering Company markets a process called Alka/Sorb that removes a major part of the mercury from offgas streams by injecting powdered lime and carbon into the offgas stream and collecting the solids in a baghouse.³

Other concepts for treating mercury in offgas should also be studied. The use of zeolites for high-temperature adsorption of mercury vapor appears to be attractive but requires additional development. Zinc dithionate and amalgamated zinc dust should be evaluated for reducing Hg^{+2} , including the insoluble sulfide form, to metallic mercury.

The Mersorb process can also be used to remove mercury from aqueous waste. Mersorb can be used over a broad pH range, and down to pH levels of 3 or 4. High concentrations of nontoxic metals in the liquid waste could make Mersorb prohibitively expensive in this application. Ion-exchange resins containing thiol groups to remove mercury from aqueous waste are commercially available. The Savannah River Site has used a thiol resin (Diolite GT-73) that was found to be very selective for mercury in the cationic form.⁴ Ionac SR-4 is another thiol resin that is commercially available. A thorough investigation should be made of technology to remove mercury from liquid streams.

6.2.2.3 Develop Analytical And Instrumentation Requirements. A working group supported by the Air Pollution Control Systems Task Force should be established to determine the analytical needs for both the liquid and gaseous APC processes and for both oxidizing and reducing atmospheres. This information would be turned over to the Analysis Task Force which would, in turn, either locate appropriate equipment in the commercial market or develop it themselves.

6.2.2.4 Identify and Define Secondary Waste Streams. A working group should be set up to identify and define all secondary waste streams emanating from the APCs.

6.2.2.5 Develop Treatment Technology For Secondary Waste Streams. A multi-site working group should be established to identify or develop treatment technology for converting secondary waste streams to forms suitable for either disposal or recycling.

6.2.2.6 Develop Acceptable Alternatives To Conventional HEPA Filters. A working group should be established within the APC Systems Task Force to evaluate and test alternatives to conventional HEPA filters. This group would (1) determine the effectiveness of HEPA filters in the removal of the submicron-sized particles that make up fumes; (2) test and evaluate continuously renewable prefilters; (3) evaluate the use of ceramic filters as an alternative to bag-house prefilters; and (4) evaluate the bag-house prefilters used with the metal melters under evaluation.

6.2.2.7 Evaluate Spray Dryer and Cooler Units. The effectiveness of spray dryers and coolers should be evaluated to determine the feasibility of using lime or carbon to perform high-temperature offgas cleanup of metals and organics, particularly dioxins.

6.2.2.8 Evaluate Systems For Removing Metals and PICs From Offgas Stream. Because metals and PICs have only recently become regulated, there is little information about them. Removal technologies to be evaluated include free-jet, wet electrostatic precipitation. One or more of these particulate and acid-gas control devices may be very effective at removing metals and PICs, so charcoal absorption may not be necessary. Particulate and acid-gas control devices should be evaluated for their effectiveness at a range of temperatures and under both oxidizing and reducing conditions.

6.2.2.9 Evaluate Cooler Units. Use of a fluidized bed cooler should be evaluated. This type of cooler, considered for cooling offgas from molten metal waste destruction, should be evaluated for use in quenching offgas from systems operating under positive pressure. The effectiveness of a fluidized bed cooler in quick quenching should be determined in this task. Bench-scale tests should be performed using both surrogate offgas with excess air and surrogate synthesis gas (containing CO and hydrogen). The evaluation should include an analysis of the expected lifetime of the fluidized bed media and the cost of disposal or recycle of this material. If this process is effective, it could be beneficially used on several other systems such as plasma and vitrification.

6.2.2.10 Develop Approach To Hydrogen Offgas Management. Hydrogen offgas produced by several of the Phase 2 systems], including plasma gasification (C-3), molten metal waste destruction (G-1), steam gasification (H-1) and mediated electrochemical oxidation (K-1), will require designs that avoid the potential for explosions. The risk of catastrophic accidents should be evaluated and understood. This task will develop safe handling operating and control procedures to minimize hazards.

6.2.2.11 Evaluate Alternative Approaches To Thermal Treatment Of Hydrogen. Hydrogen produced as an offgas product is typically mixed with a high volume of dilution air before treatment in a thermal oxidizer. An alternative method should be investigated in this task, such as energy recovery by fuel cells or gas turbines to generate electricity. Additionally, the conversion of synthesis gas to useful heat energy in a boiler or other equipment could also be investigated.

6.2.2.12 Evaluate The Delayed Offgas Release System. This concept offers the potential to capture nearly all of the combustion gases in addition to the hazardous and radioactive particulates. These adsorbents can then be monitored for hazardous and radioactive materials. If the adsorbent is found to be clean, it can be reactivated for recycling, releasing the gases to the atmosphere. As originally presented, this system used lime as the adsorbent, but, if the delayed release concept is shown to be feasible, other absorbent materials such as methanol should be evaluated. The first step in this evaluation is to combine a technical feasibility study with a cost-benefit analysis for the lime absorbent case.

6.2.3 Surrogate Waste Preparation

The surrogate waste component will prepare a mix of nonradioactive waste surrogates that closely mimics the behavior of wastes in the DOE's MLLW inventory.

6.2.4 Waste Sorting Demonstration

The waste sorting demonstration component solves problems associated with remote segregation of alpha MLLW. This component receives waste from the surrogate waste component and performs prototype-scale sorting operations, as needed, to support the requirements of the main thermal treatment unit. Typical tasks assigned to this component would include the following:

- Reporting on the feasibility of segregating the inventory as specified by the surrogate group.
- Testing the available robotics systems to determine whether automatic, noncontact sorting equipment is feasible and whether the available commercial products could be adapted to the program's needs.

6.2.4.1 Waste Sorting Task Force. A Waste Sorting Task Force made up of DOE and EPA personnel would be established by the program to evaluate solutions to problems associated with the sorting of the waste inventory into treatable parcels.

6.2.4.2 Waste Sorting Facility. A working group made up of members of the Waste Sorting Task Force would be formed to establish a waste sorting facility. This facility would evaluate automated and robotic sorting of wastes. The special needs of advanced thermal treatment systems such as fluidized bed incinerators and molten salt oxidation systems would also be addressed. (Many of these systems require removal of bulk metal from the waste stream.) Time and motion studies would be performed to assess practicality of extensive sorting prior to waste shredding.

The facilities would provide an opportunity to work with the stakeholders and regulators to develop a characterization approach that is both rational and economical. The facility would be available to evaluate the instrumentation and remote equipment that would be considered for incorporation in the integrated systems. It would help evaluate worker risk as well as determine the extent of sorting that would likely be required to maximize the efficiency of the thermal treatment unit selected.

A multi-site task group is recommended to scope out these facilities and determine their merit, schedule, and likely installation cost using either existing or new buildings.

6.2.5 Waste Characterization

The waste characterization component will solve the problems associated with characterizing incoming wastes to meet the process needs and fulfill the regulatory criteria. Sampling of the final waste form will also be a part of this component. Typical tasks assigned to this component would include the following:

- Defining a strategy for characterization of the waste in the system.

- Developing new, or refining existing, technologies to meet the needs of the project after surveying the market.
- Testing the selected concepts in the demonstration unit.

6.2.5.1 Waste Characterization Task Force. One of the early responsibilities of the program would be to form an interagency Waste Characterization Task Force made up of representatives from EPA, U.S. Department of Defense, and DOE. It would address the problems associated with the current extensive waste analysis requirements imposed on thermal treatment systems.

RCRA hazardous constituents (40CFR261, Appendix VIII) present in incinerator waste feed at concentrations in excess of 100 parts per million by weight (ppmw) must be identified by the operator. Guidance in terms of the detection limits that might be needed in the waste characterization analysis are provided in 47 CFR 122, pg. 27525 et seq. (June 24, 1982). The background discussion of this notice states that EPA estimates that constituents in the waste feed in concentrations below 100 ppmw will be routinely detected by stack gas analysis. It further states that a waste concentration of 100 ppmw probably represents a lower limit beyond which a determination of a DRE of 99.99%, as required by 40 CFR 264.343, would be difficult to document.

The waste analysis section of Interim Status Standards for Incinerators, 40 CFR 265.341, specifically requires that analyses must be made for the heating value of the waste, the halogen and sulfur content, and, unless there is written documented data showing their absence, lead and mercury. A recent publication⁵ discusses some of the statistical techniques that can be used on heterogeneous waste for quality assurance and quality control of data assessments. Additional information on this subject can be found in *Integrated Thermal Treatment System Study—Waste Characterization Requirements for Treatment and Disposal of Heterogenous Wastes*.⁶

The Waste Characterization Task Force could perform cost/benefit analyses of process-related alternatives to the currently-required extensive characterization of wastes before disposal. Typical subjects of these analyses would include the use of more robust waste treatment or more extensive APCs, or the use of more redundancy in the APCs.

6.2.5.2 Waste Characterization Facility. The program should establish a waste characterization test facility. Characterization methods would be evaluated to determine whether acceptable levels of waste characterization could be achieved using:

- Nondestructive assay such as neutron activation analysis and real-time organic vapor analysis
- Specialized neutron interrogation to identify point sources of mercury
- Shredding and bulk storage of wastes to facilitate mixing prior to sample selection and chemical assay.

6.2.6 Slag Collection

Several of the Phase 2 systems produce a molten slag that is discharged from the main thermal treatment unit. In some of the systems, a separate metal stream is discharged. The one-step processing systems include System A-7 (slagging rotary kiln), System C-2 (plasma furnace, CO₂

retention), System C-3 (plasma gasification), System G-1, (molten metal waste destruction), and System J-1 (joule-heated vitrification). The molten slag or metal from the one-step processing units is discharged into a mold. The design of this discharge system must satisfy functional and operational requirements and also the health and safety objectives. For example, an appropriate mold design should be selected that will meet the functional requirements of high temperature molten materials and operational needs of offsite transportation, storage, and disposal. This task should evaluate existing approaches to slag discharge, collection, and packaging to meet these requirements.

6.2.7 Packaging

The packaging component will develop a package system for the facility. This includes onsite and offsite handling of treated and untreated waste. A key area requiring packaging development concerns the bins used for transporting the untreated waste within the thermal treatment facility. Packages must also be defined for the final waste form. This package must meet offsite transportation, storage, and disposal requirements. Typical tasks of this component would include the following:

- Determining the needs and supply containers required for transporting wastes and intermediate waste forms between sites.
- Developing and providing containers for moving special materials (e.g., mercury adsorbent carbon canisters) within the facility.
- Developing performance-oriented packaging for transporting treated waste to disposal sites.

6.2.8 Size Reduction

The size reduction component will develop and test methods for receiving the wastes and converting them into a form that can be introduced into the incineration subsystem. Typical tasks of this component would include the following:

- Developing (from information provided by commercial vendors) a device that will adequately shred the entire range of solid wastes in the inventory.
- Developing the process required to feed the entire range of liquids to the incineration subsystem.
- Developing the process required to feed the entire range of sludges to the incineration subsystem.

6.2.8.1 Size Reduction Task Force. A Size Reduction Task Force would be established within the project using personnel from various sites. It would be the responsibility of this task force to investigate and solve problems associated with preparing the as-received waste for incineration.

6.2.8.2 Shredding Tests With Potential Vendors. Shredding tests on simulated waste to evaluate shredding capabilities and specifications. An ad hoc multi-site task group would be formed to plan and execute the shredding tests and determine the specifications for future shredding equipment, including the adaptations required to meet radioactive-handling requirements.

6.2.8.3 Evaluation Of Cryofracture. Personnel from the Waste Size Reduction Group would evaluate prior experience with the cryofracture of waste. They would assess whether technology development should be carried forward experimentally as a backup technology, particularly to support organic destruction technologies that require finely shredded feed.

6.2.9 Refractory Material Evaluation

Systems A-1 through A-7 (rotary kiln systems), C-2 (plasma furnace, CO₂ retention), C-3 (plasma gasification), G-1 (molten metal waste destruction), and J-1 (joule-heated vitrification) operate at elevated temperatures under varying pressure and atmospheric conditions. An evaluation of refractory corrosion resistance under these conditions will allow determination of operating and maintenance requirements for these systems.

6.2.10 Establish the Characteristics of INEL Iron-Enriched Basalt

INEL has performed research on the melting characteristics of iron-enriched basalt in a DC arc furnace. Assuming that this material will be processed in this facility, this study should be extended to other high-temperature processes such as the slagging rotary kiln, plasma furnace, and the molten metal waste destruction process to determine whether this material could be processed in these systems. Flow characteristics and thermal requirements under high temperature conditions should be determined and final slag characteristics must be evaluated.

6.2.11 Vitrification

The vitrification component will develop and test vitrification technologies that will serve as both the incineration technology and the primary stabilization technology. Typical tasks of this component would include the following:

- Performing bench-scale tests, as needed, to select one or two incinerator designs for installation in the demonstration facility.
- Testing one or more incinerator technologies in the demonstration facility.
- Optimizing vitrification technology to serve in the primary stabilization subsystem.
- Determining the effect of occluded carbon on the production of a satisfactory glass waste form.
- Analyzing the effect of inorganic salts on vitrification processes.

6.2.11.1 Establish A Vitrification Task Force. The program should establish a Vitrification Task Force to evaluate and develop vitrification technology for use as both primary incineration and primary stabilization.

6.2.11.2 Optimize Vitrification Of Bottom Ash And Fly Ash. The vitrification process should be optimized to produce an acceptable waste form from bottom and fly ash either individually or in combination. This work will determine the process' tolerance for variability in ash feed composition and the process operating ranges that are acceptable. The addition of contaminated soils from DOE sites should also be addressed.

6.2.11.3 Offgas Characterization. The characteristics of offgas from vitrification, both with and without PICs in the ash, should be confirmed. In addition, the ability of the process to handle PICs from ash from a pyrolyzer, as opposed to a conventional incinerator, should be examined.

6.2.11.4 Optimize Melter Design. Melter designs that allow shredded combustible waste to be directly charged to the melter should be tested. Such a melter would constitute the total thermal treatment unit at small-capacity sites. In addition, this task would evaluate the potential for a mobile unit that would be readily transportable from one site to another.

6.2.11.5 Evaluate The In-Can Melter Concept. The in-can ash melter concept should be tested to evaluate its potential for directly supporting incinerators. Variations in configurations, e.g., combining a close-coupled hearth and in-can melting, should be evaluated. The feasibility of using in-can melters at sites with low volumes of waste and of a mobile in-can melter system should also be evaluated.

6.2.11.6 Establish A Vitrification Development Facility. A vitrification development facility should be established whose primary focus would be understanding, predicting, and controlling the fate of RCRA metals and radionuclides as a function of the following parameters:

- **Melter temperature.** Thermodynamic analyses show that reactions in which salts are reduced to primary metals are favored at higher temperature and that primary metal vapor pressures increase with temperature. Existing codes such as SOLGASMIX, STEPSOL, and PYROSIM can be used to arrive at preliminary predictions that should be used as a guide to design tests of vitrification units to determine the effects of temperature.
- **Slag or glass composition.** Scoping crucible studies can be done to determine whether heavy metal retention is influenced by melt chemistry. If effects are found, then the favored compositions should be considered for vitrification flowsheet tests.
- **Carbon content of ash.** The ability to burn out carbon from the vitrification unit should be determined. Vitrification tests using an oxygen lance should be run with carbon in the feed. The extent to which carbon in the melter compromises the final waste form or complicates melter operation should be evaluated.
- **Redox conditions of melt.** Reducing conditions can promote volatilization of metals. Small-scale melter tests and crucible studies can be used to determine volatility. Release of metal compounds as a function of reducing conditions should be evaluated.
- **Cold cap conditions.** A cold top of incoming batch can capture RCRA metals. Melter tests with and without a cold top can be conducted to determine what effect a cold cap has on metal volatility. Melters should be evaluated to determine which types can be used to produce a stable cold cap.
- **Dry versus liquid feeding.** Tests with dry feeding versus liquid feeding can be done to determine impact on metal volatility. This work should be preceded by compiling and evaluating existing data from high-level waste programs at the West Valley Demonstration Project, Savannah River Site, and Hanford Site.

- **Melter configuration and type.** Melters to be considered are the fixed-hearth plasma arc, AC and DC electric arc, centrifugal hearth plasma arc, and Joule melter. The type of melter can influence metal volatility. Off-gas emissions data need to be collected on available melter systems being considered for vitrifying ash and sludge. This needs to be investigated in combination with cold cap effects.

Final waste form issues to be considered and evaluated at the vitrification development facility would include the following:

- **Treating metals in the reduced or oxidized form.** This involves choosing between the two alternatives of stabilizing the metals as either slag or glass. It may be advantageous to oxidize the RCRA metals to reduce their volatility and thereby assure compliance with land disposal restrictions. Metal oxides can dissolve into glass and are less leachable. Crucible melt tests and small melter tests can be done to address this using relevant mixed waste compositions.
- **A study of thermodynamics of slag and metal thermochemistry.** A survey of thermodynamic data would be performed to better understand the chemistries of slag and metal. Operating temperatures, redox conditions, and compositions can be optimized.

Melter design and operation issues that could be examined at the vitrification development facility include the following:

- **The range of feed compositions and physical properties.** The character of the waste to be treated by vitrification should be optimized with respect to size distribution, shape, density, and moisture content.
- **Electrode materials.** The corrosion and wear performance of electrode materials such as graphite, Inconel, molybdenum, and others, should be evaluated.
- **Corrosion of refractory materials.** Refractory materials designed to resist the effects of molten metal, basic slags (containing MgO or CaO), and acidic slags (SiO₂-bearing) should be evaluated. Refractory coatings using plasma sprays should be investigated for improved performance.
- **Maintenance requirements.** Evaluate options to minimize vitrification equipment maintenance in radioactive applications.
- **Metal withdrawal and management.** The current approach at the U.S. Bureau of Mines arc melter is to use an oxygen lance to melt the plug and drain the melter. This may not be the best option for radioactive service. Remote alternatives such as slide gates and freeze valves need to be evaluated. Also, oxidization of metals in the melter or arc furnace should be considered.
- **Evaluate Energy Sources.** Electrical melters should be compared with combustion melters. Particular attention should be paid to maintenance issues.

Issues related to using the melter for primary treatment and stabilization that could be addressed at the vitrification development facility would include the following:

- **Completeness of combustion.** The extent to which oxygen reacts with the pyrolyzed material, and with carbon within the slag or on the melted slag surface should be evaluated.
- **Effect of cold cap during combustion.** A cold cap helps to keep the volatile metals in the slag. However, gas release during combustion may interfere with the integrity of the cold cap. Testing to determine the dynamics and stability of the cold cap during combustion should be performed.
- **Ability to feed bulk metals and barrels.** Feed types and size distributions should be evaluated. The ability of various vitrification configurations to accommodate bulk objects and metals needs to be assessed.
- **Evaluate need to shred incoming waste.** Shredding offers the potential for more homogenous feed and more stable feed rates. Melter operational advantages need to be weighed against the added difficulty of shredding to determine its viability for mixed waste treatment.
- **Viability of metals as a final waste form.** Alloys produced by metal melting in a reducing atmosphere during vitrification should be tested for compliance with land disposal restrictions using the TCLP. Leaching of radionuclides also should be evaluated through MCC-1 or corrosion tests.
- **Glass development or slag composition development to optimize leaching properties and waste loading (volume reduction).** Optimal glass or ceramic compositions should be determined through a literature survey and crucible melt studies and devitrification studies.
- **Need final waste form criteria to define product properties - use performance assessment.** Windows of acceptance (i.e., performance goals) and potential use of an improved final waste form should be defined to improve margins of public acceptance, performance assessment, and product variations.
- **Leach tests and behavior of waste form in disposal environment.** The relationship between results from Product Consistency Test and American Nuclear Society⁷ tests, and fractional release rates in a burial setting and other performance assessment methods should be determined. Radionuclide release tests should be related and standards should be set. Also, testing and performance assessment should be done for RCRA metals. It should be verified that metal leach rates do not produce adverse health effects.

6.2.12 Volatile Metals

The volatile metals component will develop and test effective methods of converting volatile metals (from the inventory) into satisfactory waste forms for disposal. Typical tasks of this component would include the following:

- Optimizing lead surface cleaning methods.
- Optimizing the amalgamation technology used for mercury disposal.

6.2.13 Low-Temperature Waste Form Stabilization

The waste form stabilization component will develop and test effective stabilization methods to be applied to solid waste streams produced by the incineration and APC subsystems. Typical tasks of this component would include the following:

- Bench-scale testing of formulations for the primary and secondary stabilization techniques.
- Testing and documenting the long-term durability of the waste forms produced by the system.

6.2.13.1 Alternative Stabilization Task Force. An Alternative Stabilization Task Force should be established within the program, drawing members from various sites. It would be the responsibility of the task force to investigate and solve problems associated with the development of alternative waste stabilization methods.

6.2.13.2 Establish An Alternative Stabilization Facility. The program should establish an alternative waste stabilization facility that would carry out those tasks associated with the development and evaluation of nonvitrifier-related stabilization techniques. These tasks would include both resolving polymer stabilization issues and durability testing.

6.2.13.3 Polymer Stabilization Issues. The program should evaluate and develop techniques using polymer stabilization to encapsulate wastes in sulfur polymer cement, polyethylene, or polymer materials manufactured by Dow Chemical Company. This component of the program would also include research and development on (1) the formulation of waste and of polymer to be processed, (2) the relative merits of continuous extrusion processes and batch processes, (3) the effects of carbon in ash, and (4) the longevity of the final waste form.

At the Rocky Flats Plant, samples of polyethylene-encapsulated high-salt-content waste passed the TCLP for all target analytes at a waste loading rate of 50%. In bench-scale tests at Rocky Flats, recycled polyethylene was purchased at substantially less cost than virgin material, and it performed well for encapsulating debris.

6.2.13.4 Durability Testing. No final decision has been made with respect to the degree of durability testing that will be required for accepting stabilized final waste forms for disposal. A recent report⁸ reviews the current state of the art for evaluating final waste forms. Additional development work could be performed to screen and standardize testing of polymer-stabilized waste forms for a risk-based performance assessment, i.e., leaching test procedures to be used across the DOE complex to support risk assessment of disposal options. Procedures involved include MCC-1, TCLP, and ASTM tests B 553⁹ and C 39-72.¹⁰ Testing protocols for proving the expected long-term stability of products should be established.

6.2.13.5 Stabilization Of Special Materials. Methods for the stabilization and disposal of special materials should be developed. Particular attention should be paid to the problems associated with mercury and lead. The capability of polymer stabilization to immobilize mercury waste should be evaluated.

6.2.14 Analytical

The analytical component of the program will develop and test ways to satisfy the analytical needs of both the APC and the waste form stabilization component. Typical tasks of this component would include:

- Developing and testing analytical methods and techniques, currently unavailable, for real-time measurement of stack discharges.
- Developing improved methods of determining both the composition and quantity of compounds and components in various gas streams.

6.2.14.1 Waste Analysis Task Force. A Waste Analysis Task Force using personnel from various sites should be established by the program to identify or develop the analytical methods or instrumentation required by other components of the program. Much of this work could be coordinated with the EPA laboratories in Las Vegas and Cincinnati.

6.2.14.2 Identify Methods And Instrumentation. A major subgroup of the Analysis Task Force would be responsible for identifying or developing analytical methods and instrumentation required by others in the program. After determining the requirements of the other components of the program, this group would document the established methods and available instrumentation for meeting these needs. In particular, the group should acquire competing vendor instrumentation for on-line, real-time analysis for particulates (both total concentration and speciation), TOC, and acid gases. Where methods or instrumentation are not available, methods should be developed as required.

Typically, the need for real-time monitoring is demonstrated when evaluating the delayed offgas release concept. The whole concept of holding, testing, and then releasing offgas is based on not being able to state with confidence, in real time, that the gas has been cleaned to acceptable levels. With real-time monitors, this issue is mitigated with the additional advantages of using the monitors for operation control and demonstrating regulatory compliance. Monitors that must be in place include those that measure the concentrations of radioisotopes, combustibles, dioxins, and toxic metals (especially mercury).

6.2.14.3 Assay Of Final Waste Forms. This task would determine the feasibility of assaying containers of a final waste form containing TRU waste and comparing the results with measurements taken on the ash for validation of contents.

6.2.14.4 Evaluate Advanced Particulate Measurement Techniques. This task would evaluate the performance, and implement improvements in reliability and accuracy as necessary, for on-line instruments for measuring particulate matter. Laser sampling techniques for total particulate and for particulate characteristics are of special interest.

6.2.15 Program Integration

The program integration component, using a systems engineering approach, will maintain the thermal treatment requirements; conduct trade-off studies; and coordinate the development and test programs done by the various components. The program integration component will ensure that the demonstration program is directed in a manner that meets the goals and objectives set by the program. Key activities of this component would include the following:

- Documenting and compiling data from demonstration and test events in a manner that is useful to the architects and engineers assigned to the production facility design. This includes documenting and updating such things as system requirements, flow sheets, mass balance calculations, facility conceptual designs, and test reports.
- Performing reliability, maintainability, and availability studies.
- Performing cost trade-off studies.
- Supporting NEPA documentation, and communications and public interface activities.
- Supporting regulatory and permitting agency interface activities.
- Preparing safety analysis reports.
- Supporting program management, including task, budget, and schedule controls.

Thermal treatment is specified as a component in many large and complex waste management projects currently being considered within the DOE complex. An overwhelming amount of work is being undertaken by DOE sites. The expertise of the ITTS program could be used to quickly and efficiently integrate development data with the design of future thermal treatment systems that would best fill the client project's requirements.

6.2.15.1 Regulatory Analysis. This program will review and analyze the effect of regulations on all systems. The regulatory agencies should be involved from the start of planning and testing. The characterization facility was noted as an example where the program could work with the regulators to determine a reasonable approach to characterizing DOE solid wastes. Several Phase 2 systems might not be defined by regulatory agencies as incineration processes. Regulatory needs might be significantly reduced compared to incineration requirements. Additional work and specific coordination with other agencies will be necessary to make comparisons between the permitting and regulatory operational requirements for Phase 2 systems. In particular, the potential for permitting molten metal waste destruction as a recycling process will be evaluated.

6.2.15.2 Mobile Treatment Systems. The program should consider the range of wastes and the type of mobile units that are appropriate for sites with small volumes of waste. In this effort, the program should work with the Western Governors Association, state regulators, and EPA regional regulators to permit the use of mobile units for several locations, thereby saving on NEPA costs, permitting costs, etc.

6.3 Development Needs for Slagging Rotary Kiln (System A-7)

The slagging kiln technology is well developed. Kiln output product analysis and processing variables are key areas for further development. This includes the slag discharge system and the slag generated from DOE MLLW. Testing with the slagging kiln can be performed in conjunction with the incinerator task force and incinerator test facility described in the previous section. Bench-scale tests need to be considered for the following:

- Optimizing operation of the slagging kiln.

- Evaluating the effect of realistic feed variations on operating conditions and the probability of process upsets from different feeds or changing feeds.
- Testing of the slag produced by the kiln.

6.3.1 Slag Evaluation

Bench-scale or pilot tests should be performed with surrogate waste to evaluate the waste slag formed from the slagging kiln. The effects of variations in temperature, feed rate, and feed type on the slag should be determined. The slag should be tested for leachability and other regulatory criteria. Previous information generated by DOE and other industrial applications may be used to augment the bench-scale evaluations.

6.3.2 Slag Discharge System

Standard slagging kiln designs employ a wet discharge in which slag is discharged into a cold water bath where it fragments during the quench into small particles (1/16 to 1/4 inch). For MLLW application, a dry slag discharge system is desired where slag is discharged directly into a collection vessel. This task should evaluate existing dry discharge concepts and develop an effective design that meets the functional and operational requirements.

6.4 Development Needs of Plasma Furnace, CO₂ Retention (System C-2)

The development needs of a plasma furnace system and of a CO₂ retention system were discussed in Sections 6.2.2.12 and 6.2.11. Additional demonstration needs for System C-2 (plasma furnace, CO₂ retention), which combines these two strategies, include the following:

- Performing treatability studies using bench-scale systems.
- Developing or testing existing air exclusion approaches for the plasma reactor.
- Testing a range of feed types to evaluate the effect of realistic feed variations on operating conditions and the potential for process upsets.

6.4.1 Evaluation of Air Leakage into the Plasma Reactor

The potential for air leakage into the plasma reactor should be determined in this task. Additionally, modifications to the reactor design to minimize air leakage into the reactor should be developed. The feasibility of the CO₂ retention process and oxygen recycling are dependent on minimizing air leakage into the plasma reactor.

6.4.2 Evaluation of the Effect of Feed Type on the Plasma Furnace

The plasma furnace with CO₂ retention will require complex process controls. The success of this system will depend on the ability of the furnace to handle a wide range of feed without producing upsets that would affect the recycling of oxygen. Under this task, tests should be performed to assess the effect of feed type on the furnace operations and to evaluate process control requirements.

6.4.3 Development of Appropriate Process Controls

Process controls for the CO₂ retention system will control the fresh and recycled oxygen input to the plasma furnace. The release of a sidestream of oxygen and inert materials must be designed to prevent a buildup of inerts and to minimize unnecessary release of oxygen. The control of the oxygen recycling must be designed to prevent upsets in the plasma furnace. In this task, available process control instruments and systems will be evaluated for the control of oxygen and inerts.

6.4.4 Determine Fate of RCRA Metals and Radionuclides in Plasma Furnace, CO₂ Retention

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of metal in the CO₂ retention system. The potential for radionuclides to absorb into lime in the fluidized bed reactor and their potential to be released during calcining of the lime should be evaluated by bench-scale testing.

6.5 Development Needs for Plasma Gasification (System C-3)

The plasma gasification system still requires extensive development for use with DOE MLLW. Bench-scale tests are necessary to demonstrate waste destruction. Optimization of the reactor design for DOE MLLW with high metal content is necessary. Key areas for evaluation include feed approach, capability for processing DOE MLLW, electrode design, electrode life, reactor design, reactor discharge, and operating conditions. The following tasks need consideration:

- Performing treatability studies using bench-scale systems.
- Optimizing operation of the plasma gasification reactor by treating surrogate waste.
- Running bench-scale tests to determine volatility of metals and radionuclides at the plasma furnace's processing temperatures and in a reducing atmosphere.
- Testing a range of feed types and sizes to evaluate the effect of realistic feed variations on operating conditions and the potential for process upsets.

6.5.1 Optimize Plasma Gasification Reactor

This program should evaluate the plasma gasification reactor design and operating conditions. Reactor design must be optimized for DOE MLLW feed compositions and flow rates. Optimization should include evaluation of electrode performance, electrode maintenance needs, destruction removal efficiency, and slag removal.

6.5.2 Determine Fate of RCRA Metals and Radionuclides in Plasma Gasification Reactor

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of metal in the steam gasification system. The reducing atmosphere of plasma gasification will tend to favor metal rather than oxide formation.

6.5.3 Flexibility of Plasma Gasification Regarding Feed Variations

Bench-scale tests should be performed to determine the flexibility of plasma gasification with regard to variations in feed type and feed size. These tests will provide information on the extent of sorting and feed preparation that may be required.

6.5.4 Evaluation of Destruction Removal Efficiency

The efficiency of plasma gasification in the destruction of organic compounds in DOE MLLW should be evaluated. The removal of incomplete combustion products as well as the formation of nitrogen oxides and other regulated species should be measured.

6.5.5 Evaluation of Slag Waste

The final waste product from plasma gasification should be compared to DOE objectives. Little data are available for waste slag produced from a plasma reactor under reducing conditions. Testing of the plasma gasification reactor using surrogate waste should be performed.

6.6 Development Needs for Molten Salt Oxidation (System F-1)

The use of molten salt oxidation will require testing of several molten salt oxidation related technologies. Typical tasks would include the following:

- Performing bench-scale tests, as needed, to select an appropriate reactor design.
- Optimizing the molten salt oxidation process as a treatment technology for DOE's combustible waste.
- Evaluating the fate of RCRA and radioactive metals in the molten salt reactor.
- Performing corrosion tests to indicate reactor life.

6.6.1 Optimize MSO Reactor Design and Operation

MSO reactor design should be optimized to meet DOE objectives. Extensive information from LLNL, ORNL and vendor tests should be reviewed prior to implementing the study.

Operational issues must be resolved, including the potential for vessel and APC system corrosion. The molten salt oxidation reactor must be capable of operations with minimal corrosion because of the potential buildup of radionuclides in corroded areas.

The effect of viscosity on the molten salt process should be better understood. The viscosity of the molten salt bed affects the mass transfer rates of salt, waste, and air. The relationships of parameters that affect melt viscosity should be defined, including melt overflow rates, feed rates, air flow rates, and types of air flow sparging equipment. The viscosity of the melt is affected by the buildup of inert materials in the reactor; this buildup is controlled by removing some of the melt as overflow. Effective inert removal for the compounds contained in DOE MLLW needs to be evaluated.

6.6.2 Evaluation of the Partitioning of RCRA and Radioactive Metals

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of RCRA metals in the molten salt oxidation system. The retention of metal in the salt matrix and the final fate of metal following ash separation should be evaluated.

6.6.3 Characterization of Ash

Tests should be performed to characterize ash produced in the MSO reactor. The ash should be evaluated for carbon content and other factors that could affect ash vitrification. Significant carbon in the ash may be indicative of marginal destruction efficiency.

6.6.4 Evaluation of Waste Feed Types

Bench-scale tests should be performed to determine the flexibility of molten salt oxidation with respect to variations in feed type. These tests should provide information regarding the extent of sorting and the pre-feed batching that might be required.

6.6.5 Evaluation of MSO Salt Recycle

Salt is recycled to the MSO reactor to reduce waste volumes for disposal. The effect of recycled salt on reactor operation should be assessed, particularly to determine if the catalytic potential of the recycled salt is changed. Also, the design considerations for processing the inert materials in DOE MLLW should be developed.

6.7 Development Needs for Molten Metal Waste Destruction (System G-1)

The molten metal waste destruction component will develop and test waste destruction approaches for MLLW. Prior to embarking upon this program, an evaluation of the tests that have been performed at the vendor's facility and at DOE installations should be performed to avoid duplication of effort. Typical tasks would include the following:

- Performing treatability studies on complex mixtures of simulated waste using bench-scale systems.
- Optimizing operation of molten metal waste destruction by treating surrogate MLLW.
- Running field tests with surrogate MLLW to determine the correctness of volatility prediction techniques for the processing temperatures and reducing atmosphere of the molten metal reactor.
- Testing a range of feed types to evaluate the effect of realistic feed variations on waste form properties, offgas properties, and operating conditions, and to evaluate the probability of process upsets from different feeds or changing feeds.
- Developing a testing program to demonstrate the relationship between size reduction of the feed and treatment operations.

- Testing the effectiveness of confinement of radionuclides in pressurized systems such as molten metal.
- Developing improved solids-handling systems for both feed to and discharge from the molten metal reactor.

6.7.1 Optimize Molten Metal Reactor Design

This task should evaluate the molten metal reactor design and operating conditions. Reactor design should be optimized for DOE MLLW feed compositions and flow rates, destruction removal efficiency, and slag and metal removal. Other areas for evaluation include the feed mechanism approach, headspace requirements, reactor geometry, refractory, and reactor discharge. Bulk solids feeding by top loading or submerged lances should be developed. Slag and metal removal and handling need further development. Instrumentation must be able to function at the high temperatures of the molten metal bath.

6.7.2 Determine Fate of RCRA Metals and Radionuclides in the Molten Metal Waste Destruction Reactor

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of RCRA metals in the molten metal waste destruction system. For many metals of concern, the reducing atmosphere of molten metal waste destruction will tend to form metals rather than oxides, and the metals are generally more volatile. Reduced metals in the APC may become pyrophoric particles.

6.7.3 Flexibility of Molten Metal Waste Destruction Regarding Feed Variations

Bench-scale tests should be performed to determine the flexibility of molten metal waste destruction in handling variations in feed type and feed size. These tests should provide information regarding the extent of sorting and feed preparation that is required. The applicability of the molten metal waste destruction process to the DOE waste varieties should be demonstrated. Control of particulates, radionuclides, toxic metals, and acid gases over a range of DOE MLLW feed types and conditions should be demonstrated.

6.7.4 Evaluation of Destruction Removal Efficiency

The efficiency of molten metal in the destruction of organic compounds in DOE MLLW should be evaluated. The removal of PICs and the formation of nitrogen oxides and other regulated species should be measured. As envisioned, the molten metal process does not include secondary combustion. Testing should include an evaluation of whether secondary combustion is necessary.

6.7.5 Evaluation of Slag and Metals Produced and the Potential for Recycling

The final waste product from molten metal waste destruction should be evaluated with regard to DOE objectives. Testing of the molten metal waste destruction reactor using surrogate waste should be performed under this task. An assessment of the partitioning of radioactive metals in the slag layer produced and the potential for recycling of metals should be evaluated under this task. It is expected that metals formed from the molten metal process will have a wide range of impurities and a high carbon content. Hence, processing requirements and costs to make the molten metal products recyclable must be evaluated.

6.7.6 Evaluate the Potential for Leakage of Radionuclides from Pressurized Systems

The molten metal waste destruction reactor operates under positive pressure. Testing should be performed to determine the potential for leakage of radionuclides.

6.8 Development Needs for Steam Gasification (System H-1)

The steam gasification component will develop and test steam gasification technologies. Typical tasks of this component should include the following:

- Performing bench-scale tests, as needed, to select one or two steam gasification designs for installation in the demonstration facility.
- Optimizing steam gasification for treatment of combustible waste.
- Testing the destruction effectiveness of steam gasification.
- Evaluating the fate of RCRA and radioactive metals in the steam gasification fluidized bed reactor.
- Operation to determine the acceptable limits of noncombustibles.

6.8.1 Optimize the Steam Gasification Reactor

Bench-scale tests of steam gasification should be performed to evaluate this technology with respect to treatment of DOE MLLW. The reactor design should be optimized to meet DOE objectives. Key operating issues include control of oxygen concentration to maintain pyrolysis conditions, maintaining an evenly mixed air flow, and avoiding plugging of the bed with slag.

6.8.2 Evaluation of Destruction Removal Efficiency

The efficiency of steam gasification in the destruction of organic compounds in DOE MLLW should be evaluated. The removal of PICs and the formation of nitrogen oxides and other regulated species should be measured.

6.8.3 Evaluation of the Partitioning of RCRA and Radioactive Metals

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of RCRA metals in the steam gasification system. The reducing atmosphere of steam gasification will tend to favor metal species rather than oxides; metals are more volatile. Collection and management of metals, especially if pyrophoric, needs to be demonstrated.

6.8.4 Characterization of Bottom Ash

Tests should be performed to characterize bottom ash produced in the steam gasification reactor. The ash should be evaluated for carbon content and other factors that could affect ash vitrification.

6.8.5 Evaluation of Waste Feed Types

Bench-scale tests should be performed to evaluate the flexibility of steam gasification in handling variations in feed type. These tests will provide information regarding the extent of sorting and the pre-feed batching that is required.

6.9 Development Needs for Joule-Heated Vitrification (System J-1)

In addition to development needs identified for the vitrification process in Phase 1, the following tasks are recommended:

- Performing bench-scale tests, as needed, to optimize joule-heated melting as a treatment technology for combustible waste.
- Testing the destruction removal efficiency of the joule-heated melter for DOE MLLW.
- Evaluating the fate of RCRA and radioactive metals in the joule-heated melter.

6.9.1 Evaluate the Joule-Heated Melter Technology

The program will evaluate the joule-heated melter design and operating conditions, namely, optimal temperature, ability to accept variations in feed type, acceptable moisture content in the feed, and destruction removal efficiency. Requirements for feed characterization and additives should be established for DOE MLLW. The option of treating waste in an oxidized or reduced atmosphere should be explored. Potential operational problems should be evaluated, such as short circuiting of the electrical cell when metal settles at the reactor bottom. Particulate emissions should be measured. The fate of RCRA and radioactive metal in the melter should also be determined.

6.9.2 Evaluation of Destruction Removal Efficiency

The efficiency of the joule-heated melter in the destruction of organic compounds in DOE MLLW should be evaluated. The removal of PICs and the formation of nitrogen oxides and other regulated species should be measured.

6.9.3 Evaluation of Slag Waste

The final waste product from joule-heated vitrification must be evaluated against the final waste form criteria. The joule-heated melter should be tested using surrogate waste under this task.

6.9.4 Evaluation of Waste Feed Types and Feed Sizes

Bench-scale tests should be performed to indicate the flexibility of the joule-heated melter in handling variations in feed type and feed size. The allowable concentration of metals in the feed stream should be determined. These tests will provide information regarding the extent of sorting and feed characterization that are required.

6.10 Development Needs for Thermal Desorption (Systems K-1 and L-1)

The thermal desorption component will evaluate the feasibility of vaporizing organics from combustible and noncombustible waste for liquid organic waste treatment. Typical tasks of this component would include the following:

- Performing bench-scale tests, as needed, to select an appropriate desorber design for further testing.
- Determining the fate of mercury, radionuclides, organics, and combustible waste in the desorber.

6.10.1 Evaluate Thermal Desorber Units

Rotary kiln and other types of desorbers should be considered. Process conditions such as operating temperatures and residence times should be optimized with a surrogate feed. The effects of melting plastic on thermal desorber operation should be evaluated. Operating conditions for various feed types, including the volume and type of plastic in the feed and the volatility of representative organic compounds, should be determined. Feed sorting requirements to minimize process upsets by plastic melting and to maximize vaporized organics should also be determined. The risks of the transfer of high boiling point organics such as PCBs to the grouted waste form should be evaluated. The operational feasibility of the sorting of wastes to minimize transfer risks should be determined.

6.10.2 Determine the Fate of Metal and Organics in the Desorber

The fate of the volatile components in DOE MLLW should be determined to evaluate the effectiveness of this approach. Bench-scale testing to determine the volume of condensable and noncondensable organic gas leaving the desorber should be performed. The potential for metal and radionuclides to volatilize should also be evaluated.

6.10.3 Evaluate Grouted Desorbed Solids

Solids produced in the thermal desorber are grouted. The grouted waste should be evaluated for acceptability under the EPA debris rule. This task includes a review of the regulations to determine acceptability of the various waste streams processed in the desorber. An acceptable alternative waste processing approach, such as polymer stabilization, should be developed for the waste streams that cannot be grouted. Surrogate waste produced from the thermal desorber tests described above should be grouted and tested according to the regulations applicable to the debris rule.

6.11 Development Needs of Mediated Electrochemical Oxidation (System K-1)

This component will evaluate the MEO technology and assess the technology compared to DOE's objectives. Evaluations currently being performed at DOE's LLNL facility and PNL should be used as a starting point for the investigation. Typical tasks will include the following:

- Performing bench-scale tests to evaluate operating conditions and optimize process design.

- Testing the destruction effectiveness of mediated electrochemical oxidation.
- Evaluating the fate of RCRA and radioactive metals in the mediated electrochemical oxidation process.

6.11.1 Optimize Process Design

As a new technology for hazardous waste destruction, many aspects of MEO are under development. Bench-scale testing should be performed to evaluate the following parameters for DOE MLLW: the ratio of feed rate to the volume of electrolyte, the rate of circulation of electrolyte through multicomponent systems, the frequency of inert material removal, and the optimum temperature.

6.11.2 Destruction Efficiency of Organic Compounds

The effectiveness of destruction of organic compounds by MEO should be evaluated for DOE MLLW. The potential for volatile organics to vaporize before destruction should be determined and the high destruction removal efficiencies reported in studies should be confirmed.

6.11.3 Determine the Fate of RCRA Metals and Radionuclides in MEO Waste Streams

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of RCRA metals and radionuclides in MEO. Metals and inorganics are expected to remain in the electrolyte. Tests should be performed to verify this.

6.11.4 Determination of Acceptable Feed Types

This task has two functions. First, the flexibility of MEO in destruction of a wide range of organic compounds from various feed types should be evaluated. Second, the maximum acceptable particle size that can be processed by MEO should be determined. This will indicate the range of process streams that can be treated by MEO.

6.11.5 Recycling of Electrolyte

The sulfuric-acid cobalt electrolyte must periodically be purged of inert materials. A side stream of electrolyte is bled from the waste stream to remove a percentage of inerts. This side stream could be treated to remove metals and particulates, and to recycle the electrolyte. Effective methods of recycling metals and sulfuric acids from the electrolyte should be evaluated.

6.12 Development Needs for Supercritical Water Oxidation (System L-1)

This component will evaluate the SCWO technology and compare it to DOE's objectives. Typical tasks will include the following:

- Performing bench-scale tests to evaluate operating conditions and optimize process design.
- Evaluating the fate of RCRA and radioactive metals in the SCWO process.

6.12.1 Optimize Process Design

The SCWO process is an innovative technology, with several aspects under development. Bench-scale testing should be performed to evaluate the operating parameters for DOE MLLW, including the ratio of waste feed to the volume of water. One of the key problems to be addressed is the buildup of salt in the SCWO reactor. Methods to achieve salt removal while avoiding plugging of the discharge should be developed in this program.

6.12.2. Improve Corrosion Resistance in the SCWO Reactor

Corrosion in SCWO occurs at temperatures in the transition zone between subcritical and supercritical. Alternative engineering approaches and/or materials must be developed to reduce reactor corrosion.

6.12.3 Determination of Acceptable Feed Types

This task has three functions. First, the ability of SCWO to destroy a wide range of organic compounds should be evaluated. Second, the maximum acceptable particle size that can be processed by SCWO should be determined. Third, the operational flexibility of SCWO with respect to variation in feed type should be assessed.

6.12.4 Determine the Fate of RCRA Metals and Radionuclides in SCWO Waste Streams

Laboratory and thermodynamic modeling studies should be conducted to predict the fate of RCRA metals in SCWO. Solids are expected to remain in the brine waste. Tests should be performed to verify this.

6.12.5 Evaluate Appropriate Depressurization and Separation Technologies Following SCWO

Depressurization and separation of gas, liquid, and solids from the SCWO reactor are performed to process waste and recycle water. A review of appropriate technologies and equipment for depressurization and separation should be performed. Bench-scale tests should determine the most promising approaches.

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Slagging Rotary Kiln:

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Plasma Furnace, CO₂ Retention:

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Molten Salt Oxidation:

Energy Technology Engineering Center
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Molten Metal Waste Destruction:

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Steam Gasification:

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13080 Park Street
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MODEC
Modell Environmental Corporation
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Appendix A

Systems Preconceptual Design Figures

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Figure A1-4. Rotary kiln: PFD for mercury amalgamation and lead recovery subsystems (System A-1).

Figure A1-5. Rotary kiln: PFD for metal decontamination subsystem (System A-1).

Figure A1-6. Rotary kiln: PFD for metal melting subsystem (System A-1).

Figure A1-7. Rotary kiln: PFD for aqueous waste treatment subsystem (System A-1).

Figure A1-8. Rotary kiln: PFD for primary stabilization subsystem.

Figure A1-9. Rotary kiln: PFD for secondary stabilization subsystem.

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Figure A1-11. Rotary kiln: PFD for wet APC subsystem (System A-3).

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Figure A1-17. Rotary kiln: FAD for lead recovery subsystem (System A-1).

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Figure A1-19. Rotary kiln: FAD for metal decontamination subsystem (System A-1).

Figure A1-20. Rotary kiln: FAD for metal melting subsystem (System A-1).

Figure A1-21. Rotary kiln: FAD for aqueous waste treatment subsystem (System A-1).

Figure A1-22. Rotary kiln: FAD for primary stabilization subsystem (Systems A-1)

①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	⑰	⑱
FORKLIFT (CA)	DRUM ARLOCK (SI)	DRYER (CA)	HEATER UNIT FOR DRYER (CA)	TRANSFER DOLLY (CA)	POLYMER STORAGE SILO & FEED (CA)	WEIGH STATION (CA)	BLENDER (CA)	FEEDER (CA)	EXTRUDER (CA)	DRUM COOLING ENCLOSURE (CA)	FORCED DRAFT VENTILATION FAN (CA)	DRUM CAPPING & WASHING UNIT (CA)	ARLOCK/ LOADING FLANGE (SI)	FAH (CA)	CARBON FILTER (CA)	HEPA FILTER (CA)	INTAKE ARLOCK (SI)

CA = COMMERCIALY AVAILABLE
 NO = NEEDS DEVELOPMENT
 SI = SYSTEM INTEGRATION NEEDED

Figure A1-23. Rotary kiln: FAD for secondary stabilization subsystem (System A-1)

Figure A1-24. Rotary kiln: FAD for certify-and-ship subsystem (System A-1)

Figure A2-1. Indirectly Heated Pyrolyzer: PFD for overall system (System B-1).

Figure A2-2. Indirectly Heated Pyrolyzer: PFD for thermal treatment, APC, and primary stabilization (System B-1).

Figure A3-1. Plasma furnace: PFD for overall system (System C-1).

Figure A4-1. Fixed hearth with CO₂ retention: PFD for overall system (System D-1).

- NOTES:
1. 10% OF LIME IS DUMPED TO STABILIZATION.
 2. 90% OF LIME IS RECYCLED.
 3. FEED TO PRIMARY STABILIZATION.
 4. TRACE METALS REMOVED FROM OFFGAS IN THE AIR POLLUTION CONTROL SUBSYSTEM ARE ROUTED TO SECONDARY STABILIZATION AND NOT SHOWN ABOVE.

MAIN THERMAL TREATMENT SUBSYSTEM	MAIN THERMAL TREATMENT AIR POLLUTION CONTROL SUBSYSTEM	FLOW RATE (LB/HR)
1. NON-COMBUSTIBLE WASTE	1. COOLED OFFGAS	6,196
2. FUEL	2. COOLED OFFGAS	10,421
3. NATURAL GAS	3. COOLED OFFGAS	10,397
4. OXYGEN	4. FLYASH	24
5. ASH/SOLIDS	5. QUENCH WATER	4,225
6. OFFGAS	6. MAKEUP LIME	158
7. ASH/SOLIDS	7. SCRUBBED OFFGAS	1,667
8. SOIL MIXTURE	8. TREATED OFFGAS	1,822
9. ORGANIC LIQUIDS	9. 51	219
10. INFILTRATION AIR	10. SPEECH/SALT LIME	1,426
	11. RECYCLED WATER (SEE NOTE 1)	1,241
	12. RECYCLED WATER LIME	57
	13. RECYCLED WATER	393
	14. WATER

Figure A4-2. Fixed hearth with CO_2 retention: PFD for main thermal treatment and APC subsystems (System D-1)

Figure A5-1. Thermal desorption: PFD for overall system (System E-1)

PROCESS INPUT

NOTES

1. ASSUME GROUT TO WASTE RATES: 2 TO 1
2. ADDITIVE SOIL = 50% OF THE FEED TO PRIMARY STABILIZATION.
3. TRACE METALS REMOVED FROM OFFGAS IN ROUTED TO SECONDARY STABILIZATION AND NOT SHOWN ABOVE.

Thermal Desorption Subsystem	Flow Rate (lb/hr)	Main Thermal Treatment Subsystem	Flow Rate (lb/hr)	Main Thermal Treatment Air Pollution Control Subsystem	Flow Rate (lb/hr)	GROUT Subsystem	Flow Rate (lb/hr)
1. NON-COMBUSTIBLE WASTE	21,531	1.340	1,340	1.101	1,101	1.051	1,051
2. ADDITIVE SOIL	10,407	2.289	2,289	2.289	2,289	2.102	2,102
3. FUEL	1,800	3.289	3,289	3.289	3,289	3.969	3,969
4. AIR	31,938	4.101	4,101	4.101	4,101		
5. COOLING WATER	31,906	5.289	5,289	5.289	5,289		
6. FLYASH	32	6.289	6,289	6.289	6,289		
7. SCORBER LIQUOR	128	7.289	7,289	7.289	7,289		
8. TREATED OFFGAS	20,267	8.289	8,289	8.289	8,289		
9. SCORBER LIQUOR	13,566	9.289	9,289	9.289	9,289		
10. GROUT	1,051	10.289	10,289	10.289	10,289		
11. GROUTED DEBRIS	3,969	11.289	11,289	11.289	11,289		

Figure A5-2. Thermal desorption: PFD for thermal desorber and APC subsystem (System E-1).

FILENAME: 052152.DGN PLOT DATE: 02/23/95

Figure A6-1. Slagging rotary kiln: PFD for overall system (System A-7)

Figure A6-2. Slagging rotary kiln: PFD for main thermal treatment, air pollution control, and primary stabilization subsystems (System A-7)

Figure A6-3. Slagging rotary kiln: FAD for main thermal treatment subsystem (System A-7)

Figure A6-4. Slagging rotary kiln: FAD for air pollution control subsystem (System A-7).

FILENAME: A70NG20.NEW PLOT DATE: 01/11/95

Figure A6-5. Slagging rotary kiln: Plan view of main thermal treatment and air pollution control subsystems (System A-7).

NOTE: WALLS NOT SHOWN FOR CLARITY

EQUIPMENT LIST

- ① DUST COLLECTOR
- ② SHREDDER
- ③ RAM FEEDER
- ④ FEED HOPPER
- ⑤ CONTAMINATED SOIL ADDITIVE HOPPER
- ⑥ PORTABLE SHREDDED WASTE HOPPER
- ⑦ PORTABLE CARRIER
- ⑧ OVERHEAD CRANE

- ⑨ WASTE CONTAINER HOIST
- ⑩ SLAGGING ROTARY KILN
- ⑪ SLAG COLLECTION AND DISCHARGE CHAMBER
- ⑫ SECONDARY COMBUSTION CHAMBER
- ⑬ QUENCH CHAMBER
- ⑭ DRY FILTER BAGHOUSE
- ⑮ CARBON FILTERS
- ⑯ HEPA FILTERS
- ⑰ HYDROSONIC SCRUBBER
- ⑱ PACKED TOWER MIST ELIMINATOR
- ⑲ HEAT EXCHANGERS
- ⑳ DENOX CATALYTIC REACTOR
- ㉑ FAN AND STACK
- ㉒ WASTE SAMPLE COLLECTOR

NOT TO SCALE

FILENAME: ATDWC2D.NEW PLOT DATE: 01/11/95

Figure A6-6. Slagging rotary kiln: Perspective view of main thermal treatment and air pollution control subsystems (System A-7).

Figure A7-1. Plasma furnace, CO₂ retention: PFD for overall system (System C-2).

Figure A7-2. Plasma furnace, CO₂ retention: PFD for main thermal treatment, air pollution control, and primary stabilization subsystems (System C-2)

Figure A7-3. Plasma furnace, CO₂ retention: FAD for main thermal treatment subsystem (System C-2).

Figure A7-4. Plasma furnace, CO₂ retention: FAD for air pollution control subsystem (System C-2).

EQUIPMENT LIST

① DUST COLLECTOR	①④ QUENCHER	②⑦ CALCIUM CARBONATE STORAGE
② SHREDDER	①⑤ BAGHOUSE	②⑧ CALCINER FEED HOPPER
③ WASTE SAMPLE COLLECTOR	①⑥ CARBON FILTER	②⑨ CALCINER
④ FEED HOPPER	①⑦ HEPA FILTER	③⑩ LIME STORAGE
⑤ ADDITIVE/CONTAMINATED SOIL FEED HOPPER	①⑧ LIME SLAKER	③① DRY FILTER
⑥ PLASMA FURNACE	①⑨ DRY SCRUBBER	③② HEAT EXCHANGER/CONDENSER
⑦ ELECTRODE	②⑩ BAGHOUSE	③③ COMPRESSOR
⑧ SPARE ELECTRODE ASSEMBLY	②⑪ REHEATER	③④ DELAY TANKS
⑨ SECONDARY COMBUSTION CHAMBER	②② FLUIDIZED BED CO ₂ ABSORBER	③⑤ HEPA FILTERS
⑩ SLAG COLLECTION CHAMBER	②③ CYCLONE	③⑥ STACK
⑪ SLAG COOLING	②④ DRY FILTER	③⑦ OVERHEAD CRANE
⑫ SLAG DECONTAMINATION	②⑤ CONDENSER	③⑧ WASTE CONTAINER HOIST
⑬ SLAG INSPECTION	②⑥ COMPRESSOR	

FILENAME: C20YG20.NEW PLOT DATE: 01/11/95

Figure A7-5. Plasma furnace, CO₂ retention: Plan view of main thermal treatment and air pollution control subsystems (System C-2).

NOTE: WALLS NOT SHOWN FOR CLARITY

A-50

NOT TO SCALE

FILENAME: C20V620.NEW PLOT DATE: 01/11/95

Figure A7-6. Plasma furnace, CO₂ retention: Perspective view of main thermal treatment and air pollution control subsystems (System C-2).

Figure A8-1. Plasma gasification: PFD for overall system (System C-3).

Figure A8-2. Plasma gasification: PFD for main thermal treatment, air pollution control, and primary stabilization subsystems (System C-3).

Figure A8-3. Plasma gasification: FAD for main thermal treatment subsystem (System C-3).

Figure A8-4. Plasma gasification: FAD for air pollution control subsystem (System C-3).

FILENAME: C3DWG2D.DGN PLOT DATE: 01/11/95

Figure A8-5. Plasma gasification: Plan view of main thermal treatment and air pollution control subsystems (System C-3).

NOTE: WALLS NOT SHOWN FOR CLARITY

EQUIPMENT LIST

- ① SHREDDER
- ② PORTABLE WASTE HOPPER
- ③ WASTE FEED HOPPERS
- ④ PLASMA STEAM REACTOR
- ⑤ PLASMA TORCH
- ⑥ SLAG COLLECTION CHAMBER
- ⑦ SLAG COOLING CHAMBER
- ⑧ QUENCH COLUMN
- ⑨ DRY FILTER BAGHOUSE
- ⑩ CARBON FILTER
- ⑪ HEPA FILTER
- ⑫ HYDROSONIC SCRUBBER
- ⑬ PACKED TOWER SCRUBBER
- ⑭ THERMAL OXIDIZER
- ⑮ STACK
- ⑯ INSPECTION UNIT
- ⑰ CAPPING AND DECON UNIT
- ⑱ LIQUID WASTE TANK & PUMP
- ⑲ SOIL CONVEYOR
- ⑳ WASTE SAMPLE COLLECTOR
- ㉑ DUST COLLECTOR
- ㉒ SOIL FEED HOPPER
- ㉓ OVERHEAD CRANE
- ㉔ WASTE CONTAINER HOIST

NOT TO SCALE

FILENAME: C30WG20.DGN PLOT DATE: 01/11/95

Figure A8-6. Plasma gasification: Perspective view of main thermal treatment and air pollution control subsystems. (System C-3).

FILENAME: MSOS.DGN PLOT DATE: 02/22/95

Figure A9-1. Molten salt oxidation: PFD for overall system (System F-1).

Figure A9-2. Molten salt oxidation: PFD for main thermal treatment, air pollution control, and salt recycling subsystems (System F-1).

Figure A9-3. Molten salt oxidation: PFD for primary stabilization subsystem (System F-1).

→ PRIMARY MATERIAL FLOW
 --- SECONDARY MATERIAL FLOW

1	LIFT HOIST ICA	2	SHREDDER INLET AIRLOCK ISI	3	COARSE AND FINE SHREDDER ISI	4	SHREDDER OUTLET AIRLOCK AND LUNGE FLANGE ICI	5	PORTABLE WASTE HOPPER ICI	6	TRANSFER DAILY HOPPER ICA	7	BAGHOUSE ICA	8	GANTRY ROBOT ISI	9	WASTE SAMPLER DEVICE ISI
10	PNEUMATIC TUBE CONVEYOR ISI	11	UNLOADING AIRLOCK AND FLANGE ICI	12	WASTE FEEDER ICA	13	INTAKE HOPPER ISI	14	MOLTEN SALT UNIT ICA	15	PORTABLE ASH HOPPER ICI	16	ASH COOLER ISI	17	AIR SUPPLY FAN ICA		

CA = COMMERCIALY AVAILABLE
 NO = NEEDS DEVELOPMENT
 SI = SYSTEM INTEGRATION NEEDED

Figure A9-4. Molten salt oxidation: FAD for main thermal treatment subsystem (System F-1).

Figure A9-5. Molten salt oxidation: FAD for air pollution control subsystem (System F-1).

Figure A9-6. Molten salt oxidation: FAD for salt recycling subsystem (System F-1).

Figure A9-7. Molten salt oxidation: FAD for primary stabilization subsystem (System F-1).

EQUIPMENT LIST

① PRIMARY AND SECONDARY SHREDDER	⑪ ASH COOLING AND COLLECTION CHAMBER	⑲ EVAPORATIVE CRYSTALLIZER
② WASTE SAMPLE COLLECTOR	⑫ SALT DRYER TRAY	⑳ HEAT EXCHANGER AND CONDENSER
③ DUST COLLECTOR	⑬ HAMMERMILL	㉑ PARTIAL QUENCHER
④ LIQUID WASTE STORAGE TANK	⑭ SOLUTION MIXER TANK & TRANSFER PUMP	㉒ BAGHOUSE FILTER
⑤ TERTIARY SHREDDER	⑮ FILTER	㉓ CENTRIFUGAL SCRUBBER
⑥ AUGER FEEDER	⑯ PAN DRYER	㉔ REHEATER
⑦ FEED HOPPER	⑰ CENTRIFUGE	㉕ CHARCOAL FILTERS
⑧ MOLTEN SALT OXIDATION REACTOR	⑱ WATER EVAPORATION TANK	㉖ HEPA FILTERS
⑨ WASTE CONTAINER HOIST	㉑ EVAPORATIVE CRYSTALLIZER	㉗ FAN
⑩ OVERHEAD CRANE	㉒ HEAT EXCHANGER AND CONDENSER	㉘ STACK
		㉙ PORTABLE SHREDDED WASTE HOPPERS
		㉚ HOLDING RESERVOIR

FILENAME: F10W620.NEW PLOT DATE: 01/12/95

Figure A9-8. Molten salt oxidation: Plan view of main thermal treatment and air pollution control subsystems (System F-1).

FILENAME: F10VC20.NEW PLOT DATE: 01/12/95

Figure A9-9. Molten salt oxidation: Perspective view of main thermal treatment and air pollution control subsystems (System F-1).

Figure A10-1. Molten metal waste destruction: PFD for overall system (System G-1).

Figure A10-2. Molten metal waste destruction: PFD for main thermal treatment, air pollution control, and primary stabilization subsystems (System G-1).

①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮
LIFT HOIST (CA)	SHREDDER INLET AIRLOCK (SI)	SHREDDER (CA)	WASTE SAMPLER DEVICE (SI)	SHREDDER OUTLET AIRLOCK AND LOADING FLANGE (SI)	PORTABLE WASTE HOPPER (SI)	TRANSFER DOLLY (CA)	PNEUMATIC TUBE CONVEYOR (SI)	BAGHOUSE (SI)	GANTRY ROBOT (ND)	INPUT WASTE BLENDING TANK (ND)	LIQUID WASTE FEED TANK (CA)	PULVERIZED SOLIDS FEED SYSTEM (ND)	FLUX FEEDS SYSTEM (ND)	BULK WASTE FEEDER (CA)
⑯	⑰	⑱	⑲	⑳	㉑	㉒	㉓	㉔	㉕	㉖	㉗	㉘	㉙	㉚
UNLOADING AIRLOCK AND FLANGE (ND)	INTAKE HOPPER (CA)	LOCK HOPPER (CA)	CEP REACTOR (ND)	SELECTIVE SLAG/ METAL REMOVAL SYSTEM (ND)	DRY FILTER (SI)	SLAG COOLING CHAMBER (CA)	SLAG/ METAL REMOVAL CHAMBER (ND)	CAPPING AND DECON (SI)	MELTER TILT MECHANISM (CA)	FLUXED BED COOLER (CA)	CYCLONE SEPARATOR (CA)	PNEUMATIC FEED SYSTEM (ND)	ROTATING JOINT (CA)	HEATING SOURCE (CA)

CA - COMMERCIALY AVAILABLE
ND - NEEDS DEVELOPMENT
SI - SYSTEM INTEGRATION NEEDED

Figure A10-3. Molten metal waste destruction: FAD main thermal treatment system (System G-1).

Figure A10-4. Molten metal waste destruction: FAD for air pollution control subsystem (System G-1).

EQUIPMENT LIST

① SHREDDER	⑦ SLAG COOLING CHAMBER	⑬ PACKED TOWER SCRUBBER	⑲ WASTE SAMPLE COLLECTOR	⑲ CONDENSER
② TRANSPORTABLE WASTE HOPPER	⑧ FLUIDIZED BED COOLER	⑭ THERMAL OXIDIZER	⑳ DUST COLLECTOR	⑳ SIZE REDUCTION TABLE
③ ADDITIVE FEED HOPPERS	⑨ DRY FILTER BAGHOUSE	⑮ STACK	㉑ OVERHEAD CRANE	㉑ SLAVE MANIPULATOR
④ MOLTEN METAL REACTOR	⑩ CARBON FILTER	⑯ INSPECTION UNIT	㉒ ADDITIVE STORAGE	㉒ WASTE CONTAINER HOIST
⑤ SLAG/METAL REMOVAL PORT	⑪ HEPA FILTER	⑰ DECONTAMINATION UNIT	㉓ WASTE BLENDER	㉓ HYDRAULIC MANIPULATOR
⑥ SLAG METAL REMOVAL SYSTEM	⑫ VENTURI SCRUBBER	⑱ LIQUID WASTE TANK & PUMP	㉔ CYCLONE SEPARATOR	

FILENAME: G10WG20.NEW PLOT DATE: 01/12/95

Figure A10-5. Molten metal waste destruction: Plan view of main thermal treatment and air pollution control subsystems (System G-1) .

FILENAME: G10X20.NEW PLOT DATE: 01/12/95

Figure A10-6. Molten metal waste destruction: Perspective view of main thermal treatment and air pollution control subsystems (System G-1).

Figure A11-1. Steam gasification: PFD for overall system (System H-1).

Figure A11-3. Steam gasification: PFD for primary stabilization subsystem (System H-1).

Figure A11-4. Steam gasification: FAD for main thermal treatment subsystem (System H-1).

Figure A11-6. Steam gasification: FAD for syngas oxidation subsystem (System H-1).

Figure A11-7. Steam gasification: FAD for primary stabilization subsystem (System H-1).

Figure A11-8. Steam gasification: Plan view of main thermal treatment and air pollution control subsystems (System H-1).

Figure A11-9. Steam gasification: Perspective view of main thermal treatment and air pollution control subsystems (System H-1).

Figure A12-1. Joule-heated vitrification: PFD for overall system (System J-1).

Figure A12-2. Joule-heated vitrification: PFD for main thermal treatment, air pollution control, and primary stabilization subsystems (System J-1).

Figure A12-3. Joule-heated vitrification: FAD for main thermal treatment and primary stabilization subsystems (System J-1).

Figure A12-4. Joule-heated vitrification: FAD for air pollution control subsystem (System J-1).

EQUIPMENT LIST

- ① SHREDDER
- ② DUST COLLECTOR
- ③ SOIL FEED HOPPER
- ④ JOULE-HEATED VITRIFIER
- ⑤ SLAG COLLECTION AND COOLING CHAMBER
- ⑥ HEPA FILTER
- ⑦ HYDROSONIC SCRUBBER
- ⑧ QUENCH COLUMN
- ⑨ DRY FILTER BAGHOUSE
- ⑩ CARBON FILTER
- ⑪ PACKED TOWER SCRUBBER
- ⑫ REHEATER
- ⑬ DENOX REACTOR
- ⑭ STACK
- ⑮ SECONDARY COMBUSTION CHAMBER (SCC)
- ⑯ DECONTAMINATION UNIT
- ⑰ PORTABLE WASTE HOPPER
- ⑱ SOIL ADDITIVE CONVEYOR
- ⑲ OVERHEAD CRANE
- ⑳ WASTE CONTAINER HOIST
- ㉑ HEAT EXCHANGER
- ㉒ WASTE SAMPLE COLLECTOR
- ㉓ SCREW FEEDER
- ㉔ MIXED WASTE HOPPER
- ㉕ INSPECTION UNIT

SCALE: $\frac{1}{16}'' = 1' - 0''$

FILENAME: J10Y020-NEW PLOT DATE: 01/12/95

Figure A12-5. Joule-heated vitrification: Plan view of main thermal treatment and air pollution control subsystems (System J-1).

NOTE: WALLS NOT SHOWN FOR CLARITY

EQUIPMENT LIST

①	SHREDDER
②	DUST COLLECTOR
③	SOIL FEED HOPPER
④	JOULE-HEATED VITRIFIER
⑤	SLAG COLLECTION AND COOLING CHAMBER
⑥	HEPA FILTER
⑦	HYDROSONIC SCRUBBER
⑧	QUENCH COLUMN
⑨	DRY FILTER BAGHOUSE
⑩	CARBON FILTER
⑪	PACKED TOWER SCRUBBER
⑫	REHEATER
⑬	DENOX REACTOR
⑭	STACK
⑮	SECONDARY COMBUSTION CHAMBER (SCC)
⑯	DECONTAMINATION UNIT
⑰	PORTABLE WASTE HOPPER
⑱	SOIL ADDITIVE CONVEYOR
⑲	OVERHEAD CRANE
⑳	WASTE CONTAINER HOIST
㉑	HEAT EXCHANGER
㉒	WASTE SAMPLE COLLECTOR
㉓	SCREW FEEDER
㉔	MIXED WASTE HOPPER
㉕	INSPECTION UNIT

NOT TO SCALE

FILENAME: J10W20.NEW PLOT DATE: 01/12/95

Figure A12-6. Joule-heated vitrification: Perspective view of main thermal treatment and air pollution control subsystems (System J-1).

Figure A13-1. Thermal desorption and mediated electrochemical oxidation: PFD for overall system (System K-1).

Figure A13-2. Thermal desorption and mediated electrochemical oxidation: PFD for main thermal treatment and air pollution control subsystems (System K-1).

Figure A13-3. Thermal desorption and mediated electrochemical oxidation: PFD for organic liquid waste treatment subsystem (System K-1).

Figure A13-4. Thermal desorption and mediated electrochemical oxidation: FAD for main thermal treatment, air pollution control, and grout stabilization subsystems (System K-1).

CA - COMMERCIALLY AVAILABLE
ND - NEEDS DEVELOPMENT
SI - SYSTEM INTEGRATION

EQUIPMENT LIST

① SHREDDER	⑪ CARBON FILTER	⑲ POLYMER DRUM
② STACK	⑫ HEPA FILTERS	⑳ DISTILLATION COLUMN
③ WASTE FEED HOPPER	⑬ ORGANIC LIQUID TANK	㉑ THERMAL OXIDIZER
④ THERMAL DESORBER	⑭ MERCURY COLLECTION VESSEL	㉒ PORTABLE WASTE HOPPER
⑤ DISCHARGE HOPPER	⑮ CHARACTERIZATION TANK	㉓ DUST COLLECTOR
⑥ WASTE HOPPER	⑯ ELECTROLYTE RECIRCULATION TANKS	㉔ WASTE CONTAINER HOIST
⑦ DRY METAL FILTER	⑰ OVERHEAD CRANE	㉕ PUG MILL
⑧ BATCH TANK	⑱ CHLORINE SCRUBBER	㉖ INSPECTION STATION
⑨ PRIMARY CONDENSER	㉑ MED CELLS (30)	㉗ DECONTAMINATION STATION
⑩ SECONDARY CONDENSER	㉒ BATCH PRECIPITATION TANK	㉘ SAMPLE COLLECTOR
		㉙ FILTER PRESS

FILENAME: K10WC2D.NEW PLOT DATE: 01/12/95

Figure A13-6. Thermal desorption and mediated electrochemical oxidation: Plan view of main thermal treatment and air pollution control subsystems (System K-1).

Figure A13-7. Thermal desorption and mediated electrochemical oxidation: Perspective view of main thermal treatment and air pollution control subsystems (System K-1).

Figure A14-1. Thermal desorption and supercritical water oxidation: PFD for overall system (System L-1).

Figure A14-2. Thermal desorption and supercritical water oxidation: PFD for main thermal treatment and air pollution control subsystems (System L-1).

Figure A14-3. Thermal desorption and supercritical water oxidation: PFD for organic liquid waste treatment subsystem (System L-1).

Figure A14-4. Thermal desorption and supercritical water oxidation: FAD for main thermal treatment, air pollution control and grout stabilization subsystems (System L-1).

Figure A14-5. Thermal desorption and supercritical water oxidation: FAD for organic liquid waste treatment subsystem (System L-1).

EQUIPMENT LIST

① SHREDDER	⑫ HEPA FILTER	②③ THERMAL OXIDIZER
② STACK	⑬ ORGANIC LIQUID TANK	②④ PORTABLE WASTE HOPPER
③ WASTE FEED HOPPER	⑭ MERCURY COLLECTION VESSEL	②⑤ DUST COLLECTOR
④ THERMAL DESORBER	⑮ HEAT EXCHANGER	②⑥ WASTE CONTAINER HOIST
⑤ DISCHARGE HOPPER	⑯ SUPERCritical WATER REACTOR	②⑦ PUG MILL
⑥ WASTE HOPPER	⑰ OVERHEAD CRANE	②⑧ INSPECTION STATION
⑦ DRY METAL FILTER	⑱ VAPOR-LIQUID PHASE SEPARATOR	②⑨ DECONTAMINATION STATION
⑧ BATCH TANK	⑲ EVAPORATIVE WIPE FILTER	③① SAMPLE COLLECTOR
⑨ PRIMARY CONDENSER	⑳ COOLING HEAT EXCHANGER	③② ION EXCHANGE UNIT
⑩ SECONDARY CONDENSER	㉑ EQUALIZING VESSEL	③③ LIQUID PHASE CARBON
⑪ CARBON FILTER	㉒ FAN	③④ ADDITIVE FEED PUMPS

SCALE: $\frac{1}{16}" = 1'-0"$

FILENAME: L1DWG20.NEW PLOT DATE: 01/12/95

Figure A14-6. Thermal desorption and supercritical water oxidation: Plan view of main thermal treatment and air pollution control subsystems (System L-1).

NOTE: WALLS NOT SHOWN FOR CLARITY

FILENAME: L10YG20.NEW PLOT DATE: 01/12/95

Figure A14-7. Thermal desorption and supercritical water oxidation: Perspective view of main thermal treatment and air pollution control subsystems (System L-1).

Appendix B

ITTS Study Mass Balance Modeling

Appendix B

ITTS Study Mass Balance Modeling

This appendix contains details of the mass balance calculations performed for the nineteen systems in the ITTS study. Mass and energy balances were performed using ASPEN PLUS for the nineteen systems and the metal melters. ASPEN modeling included the following subsystems only: the main thermal treatment, APC, primary stabilization, and metal melting. Details of the ASPEN calculations are found in a separate report.¹

The overall mass balances for the nineteen systems are summarized in Table B-1. Data for systems not modeled with ASPEN come from the Phase 1 report,² updated for consistency with the Phase 2 assumptions. A discussion of the mass balance performed specifically on aqueous waste is presented after the subsystem descriptions.

Primary Treatment Subsystem

The primary treatment subsystem, as modeled by ASPEN, is comprised of the primary thermal treatment unit (rotary kiln, plasma furnace, molten salt unit, etc.), secondary combustion chamber (SCC), water quench, gas scrubber, and all other ancillary equipment and processing units.

Depending on the robustness of the primary treatment unit, it can accept a combination of the following inputs: combustible waste (660 lb/hr), noncombustible waste (1,340 lb/hr), soil (used as an additive in the vitrification step, typically about 500 lb/hr), and metal with entrained contamination (149 lb/hr). The waste streams that are not input directly to the primary treatment unit are fed to the other units associated with the primary thermal treatment subsystem. These units are typically the vitrifier, metal melter, liquid organic waste treatment, etc. The liquid organic waste subsystems (K-1 and L-1) accept small subsets of the combustible waste stream (51 lb/hr) and aqueous treatment waste streams (16 lb/hr). Details are found on the system flow sheets in the main body of the report (see Figures 3-2 through 3-20).

Depending on which primary treatment unit is to treat the waste, the primary treatment subsystem also requires additional input streams to operate the units within the primary treatment subsystem. These inputs include air or oxygen for combustion, natural gas for primary and secondary combustion, sodium hydroxide for gas scrubbing, primary cooling water, and water for gas quench and scrubbing. Some primary treatment subsystems have other, more specific input requirements.

Gas scrubbers for the primary treatment subsystems were modeled to allow sufficient water input for a total dissolved solids concentration of 5% in the scrubber bottoms, assuming no condensation of water in the gas stream. This approach controls the total volume of water used in the scrubber system to a manageable amount. Heat exchangers would be required to maintain the scrubber water volume.

Metal Melting Subsystem

The metal melter is used for metallic waste that is contaminated with radioactivity that is entrained with the metal and is not separable from the waste. This contaminated metal can be input to the primary treatment unit or treated in a separate metal melter. Input to the metal melter is 149 lb/hr, most of which is iron. A detailed breakdown of the input to the metal melter is found in the ASPEN report.¹

Table B-1. Overall mass balances for nineteen ITTS systems.

[illegible]

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS								
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
	PROCESS INPUTS								
MAIN THERMAL TREATMENT SUBSYSTEM (MTT)									
H ₂ O	482	1,824	526	1	663	485			
CH ₄	1	1	1	261	1	1	568		
O ₂		1,830		1,455				290	
Air	7,859		7,859		7,878	7,859	18,326		6,239
Air Inleakage	2,695	2,695	2,695	2,695	2,695	2,695	2,695	224	
Soil	498	498	370	498		495	564		482
VITRIFIER									
Soil								498	
Water	91	91	68	91		90			
CH ₄	15	15	11	15		15			
O ₂	197	197	146	197		196		23	
Air	15	15	11	15		15			
SCC									
CH ₄	418	137	419	355	424	418	208		
O ₂		658		1,712				834	
Air	8,663		8,691		8,790	8,666	4,319		1
WATER									
Primary Quench	10221	4890		13434	10354	10224	15425	1411	3549
Secondary Quench				926					
Primary Scrubber	2,259	2,259	2,259		2,259	2,259	2,259	2,259	2,259
Secondary Scrubber									
OTHER									
NaOH	78	78	76		78	2	78	78	78
Na ₂ CO ₃									
CaO				374					
Electrolyte(Water & CoSO ₄)									
Input to Indirect Heater									
Air to Catalytic Oxidizer									
CH ₄									
Air									
Subtotal - MTT	33,492	16,188	23,132	22,029	33,142	33,420	44,442	6,617	12,608
AUXILIARY SUBSYSTEMS									
METAL MELTING (MM)									
Air	25	25	25	25	25	25	0	25	0
Water	19	19	19	19	19	19	0	19	0
Soil + Flux	10	10	10	10	10	10	0	10	0
Subtotal - MM	54	54	54	54	54	54	0	54	0

Table B-1. (continued).

TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
LEAD RECOVERY (PbR)									
APC Water (use recycle)	14	14	14	14	14	14	14	14	14
Fuel									
Air	21	21	21	21	21	21	21	21	21
Blast Water	29	29	29	29	29	29	29	29	29
Soil	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Subtotal - PbR	64.26	64.26	64.26	64.26	64.26	64.26	64.26	64.26	64.26
AQUEOUS WASTE TREATMENT (AQ)									
Resins & Activated Carbon	810.96	600.96	199.56	942.6	827.1	798.36	1117.02	281.22	385.56
Additives (0.051 lb/lb input)	0	0	0	0	0	0	0	0	0
Rinse Water for 2° Stabilization	403.25	298.25	97.55	469.07	411.32	396.95	556.28	138.38	190.55
Subtotal - AQ	1214.208	600.96	199.56	942.6	827.1	798.36	1117.02	281.22	385.56
MERCURY AMALGAMATION (HgA)									
Additives (0.1 lb/lb)	5	5	5	5	5	5	5	5	5
Nitrogen (0.22 lb/lb)	11	11	11	11	11	11	11	11	11
Air (0.60 lb/lb)	30	30	30	30	30	30	30	30	30
Water (0.58 lb/lb)	29	29	29	29	29	29	29	29	29
Subtotal - HgA	75	75	75	75	75	75	75	75	75
TOTAL PROCESS INPUTS	34,899	15,982	23,525	23,165	34,162	34,411	45,698	6,091	13,133
INTERNAL SYSTEM RECYCLE									
Scrubber Liquor from Scrubber to Aqueous Waste Treatment	13,436	9,936	3,246	15,630	13,705	13,226	18,537	4,607	6,346
Sludge from Pb Recovery to Aqueous Waste Treatment	0	0	0	0	0	0	0	0	0
Resins from Aqueous Waste Treatment to Thermal Treatment	824	611	203	958	841	812	1,136	286	392
Hg Amalgamation Solids to Thermal Treatment	18	18	18	18	18	18	18	18	18
Water from Metal Decontamination to Recycle	112	112	112	112	112	112	112	112	112
TOTAL INTERNAL SYSTEM RECYCLE (Not including recycle to thermal treatment)	13,548	10,048	3,358	15,742	13,817	13,338	18,649	4,719	6,458
TOTAL INPUT	51,375	28,958	29,810	41,834	50,907	50,677	67,275	13,738	22,518

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS								
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
	SYSTEM OUTPUT								
	MAIN THERMAL TREATMENT (MTT) SUBSYSTEM OUTPUT								
SOLIDS									
Slag	1,495	1,495	1,109	1,495		1,485	1,691	1,495	1,450
Debris									
Nonvitrified Ash			277		1,078				
Metal						8			170
Trace Metals	4	4	4	4	4	4	4	4	4
Na ₂ CO ₃									
NaCl/NaF						0.24			
HCl (50% in Water)						140			
CaO				317					
CaCl ₂ , CaSO ₄				113					
Subtotal - Solids	1,499	1,499	1,390	1,929	1,082	1,637	1,695	1,499	1,624
	Main Thermal Treatment APC								
LIQUIDS & DISSOLVED GASES									
Scrubber Water	13,323	9,823	3,133	15,630	13,592	13,224	18,424	4,494	6,233
Dissolved Salts	113	113	113		113	2	113	113	113
Dissolved Gases									
O ₂	2	5		2	2		2		
N ₂	13	6	3	21	13		18	1	6
CO ₂	23	47	5		23		35	74	17
SO ₂		1						1	
Electrolyte(Water & CoSO ₄)									
Subtotal - Liquids & Dissolved Gases	13,474	9,995	3,254	15,653	13,743	13,226	18,592	4,683	6,369
GASES									
O ₂	1,625	1,387	1,627	156	1,632	1,627	1,489	16	258
N ₂	14,730	2,062	14,762	2,046	14,842	14,746	19,523	171	4,781
CO ₂	2,364	1,569	2,378	2,929	2,352	2,387	3,366	1167	1,236
H ₂ O Vapor	1,478	357	1,482	996	1,488	1,479	1,923	77	485
SO ₂	3	2	3		3	3	3	2	2
Subtotal - Gases	20,200	5,377	20,252	6,127	20,317	20,242	26,304	1,433	6,762
INDIRECT-FIRED EXHAUST									
O ₂									
N ₂									
CO ₂									
H ₂ O Vapor									
Subtotal - Indirect-Fired Exhaust	0	0	0	0	0	0	0	0	0
TOTAL - MTT Subsystems Output	35,173	16,871	24,896	23,709	35,142	35,105	46,591	7,616	14,755

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS								
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
	AUXILIARY SUBSYSTEM OUTPUTS								
Metal Decontamination (MD)									
Clean Metal	463	463	463	463	463	463	463	463	463
Grit	5	5	5	5	5	5	5	5	5
Water	112	112	112	112	112	112	112	112	112
Subtotal - Metal Decon	580	580	580	580	580	580	580	580	580
Metal Melting									
Clean Metal	134	134	134	134	134	134	0	134	0
Treated Offgas	46	46	46	46	46	46	0	46	0
Slag	23	23	23	23	23	23	0	23	0
Subtotal - Metal Melting	203	203	203	203	203	203	0	203	0
Lead Recovery									
Clean Lead	20	20	20	20	20	20	20	20	20
Offgas	35	35	35	35	35	35	35	35	35
Water	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
Sludge	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Lead Ingots	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Slag	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Subtotal - Lead Recovery	90.28	90.28	90.28	90.28	90.28	90.28	90.28	90.28	90.28
Primary Stabilization									
Offgas	318	318	236	318		316			
Subtotal - Primary Stab.	318	318	236	318	0	316	0	0	0
Aqueous Waste Treatment									
Treated Water (0.977 lb/lb aqueous waste, 0.899 lb/lb scrubber liquor)	12,157.12	9,010.62	2,996.31	14,129.53	12,398.96	11,968.33	16,742.92	4,219.85	5,783.21
Resins, Organics, Spent Carbon (0.061 lb/lb aqueous waste, 0.061 lb/lb scrubber liquor)	824.476	610.976	202.886	958.31	840.885	811.666	1135.637	285.907	391.986
Treated Offgas (0.007 lb/lb aqueous waste)	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Concentrated Liquids (0.007 lb/lb aqueous waste, 0.10 lb/lb scrubber liquor)	1,231.16	881.16	212.16	1,563.56	1,258.06	1,321.16	1,741.26	348.26	522.16
Salts from Concentrated Liquids	113.00	113.00	113.00	0.00	113.00	2.00	113.00	113.00	113.00
Rinse Water from 2nd Stab.	403.25	298.25	97.55	469.07	411.32	396.95	556.28	138.38	190.55
Subtotal - Aqueous Waste Treatment	14,729.57	10,616.32	3,524.92	16,651.96	14,611.46	14,103.72	19,733.38	4,967.58	6,810.92

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS								
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
Mercury Amalgamation									
Amalgamated Waste (0.21 lb/lb Input)	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Offgas (1.94 lb/lb Input)	97	97	97	97	97	97	97	97	97
Contaminated Solids (0.35 lb/lb Input)	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
Subtotal - Mercury Amalgamation	125	125	125	125	125	125	125	125	125
Special Waste	153	153	153	153	153	153	153	153	153
SUBTOTAL - Auxiliary									
Subsystem Outputs	16,198.85	12,085.60	4,912.09	18,121.24	15,762.74	15,570.87	20,681.66	6,118.86	7,759.20
SUBTOTAL - Offgas	20,696.56	5,873.56	20,866.45	6,623.56	20,495.56	20,736.43	26,436.56	1,811.56	6,894.56
TOTAL OUTPUT	51,371.85	28,956.60	29,808.09	41,830.24	50,904.74	50,676.11	67,272.66	13,733.86	22,514.20
MASS BALANCE (Input - Output)	2.92	0.92	1.92	3.92	1.92	0.68	1.92	3.92	3.92
Volume Reduction Ratio Calculation									
Densities (lb/ft ³)									
Input Waste	64	64	64	64	64	64	64	64	64
Soil	67	67	67	67	67	67	67	67	67
Metal (Input)	26	26	26	26	26	26	26	26	26
Metal (Output)	480	480	480	480	480	480	480	480	480
Aqueous Liquid	62	62	62	62	62	62	62	62	62
Slag	187	187	187	187	187	187	187	187	187
Polymerized Salt	80	80	80	80	80	80	80	80	80
Polymerized Ash/Metal/Salt	94	94	94	94	94	94	94	94	94
Polymerized Lime	96.5	96.5	96.5	96.5	96.5	96.5	96.5	96.5	96.5
Grouted Debris	126.6	126.6	126.6	126.6	126.6	126.6	126.6	126.6	126.6
Stab Hg Amalgam	732.96	732.96	732.96	732.96	732.96	732.96	732.96	732.96	732.96
Volume Solids In (ft ³ /hr)	45.73	45.73	45.73	45.73	45.73	45.73	45.73	45.73	45.73
Mass Slag Out (lb/hr)	1,518.78	1,518.78	1,132.78	1,518.78	23.78	1,508.78	1,691.78	1,518.78	1,450.78
Mass Nonvitrified Ash Out	0.00	0	277	0	1,078	0	0	0	0
Mass Special Waste (not stab)	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00
Mass Residues from MD	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Mass MTT Debris & PbR Sludge Out (lb/hr)	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Mass Metal/Pb Out (lb/hr, clean)	621.50	621.50	621.50	621.50	621.50	629.50	487.50	621.50	657.50
Mass Salts Out (lb/hr)	118.00	118.00	118.00	118.00	118.00	7.24	118.00	118.00	118.00
Mass Lime Out (lb/hr)	0.00	0	0	317	0	0	0	0	0
Mass Stab Hg Amalgam Out	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50

Table B-1. (continued).

TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
Volume Slag Out (ft ³ /hr)	8.12	8.12	6.06	8.12	0.13	8.07	9.05	8.12	7.76
Vol Stab Nonvitrified Ash Out (ft ³ /hr)	0.00	0.00	5.89	0.00	22.94	0.00	0.00	0.00	0.00
Volume Special Wastes (not stabilized)(ft ³ /hr)	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Vol Stab MD Residues Out (ft ³ /hr)	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Volume Stab MTT Debris & PbR Sludge Out (ft ³ /hr)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Volume Metal/Pb Out (ft ³ /hr)	1.29	1.29	1.29	1.29	1.29	1.31	1.02	1.29	1.37
Volume Stabilized Salts Out (ft ³ /hr)	2.95	2.95	2.51	2.45	2.95	0.18	2.95	2.95	2.95
Volume Stabilized Lime Out (ft ³ /hr)	0.00	0.00	0.00	6.57	0.00	0.00	0.00	0.00	0.00
Vol Stab Hg Amalgam Out	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Volume Solids Out to Disposal(ft ³ /hr) (Includes 1:1 polymer:ash, 1:1 polymer:salt, 2:1 grout:debris)	13.6	13.6	17.0	19.7	28.5	10.8	14.5	13.6	13.2
Volume Metal to Recycle (ft ³ /hr)	1.29	1.29	1.29	1.29	1.29	1.31	1.02	1.29	1.37
Waste Volume Reduction Ratio (In/Out)	3.37	3.37	2.69	2.33	1.60	4.26	3.16	3.37	3.48
Mass Processed Waste Out (lb/hr)									
Slag	1518.78	1518.78	1132.78	1518.78	23.78	1508.78	1691.78	1518.78	1450.78
Stabilized Ash (1:1 polymer:ash)	0.00	0.00	554.00	0.00	2156.00	0.00	0.00	0.00	0.00
Special Waste	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00
Stabilized MD Residue (1:1 polymer:residue)	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Stabilized Debris & PbR Sludge (2:1 grout:debris)	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Stabilized Salts (1:1 polymer:salt)	236.00	236.00	236.00	236.00	236.00	14.48	236.00	236.00	236.00
Stabilized Lime (1:1 polymer:lime)	0.00	0.00	0.00	634.00	0.00	0.00	0.00	0.00	0.00
Hg Amalgam	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50
Total Mass Processed Wastes Out (lb/hr)	1929.18	1929.18	2097.18	2563.18	2590.18	1697.66	2102.18	1929.18	1861.18
Waste Mass Reduction Ratio (In/Out)	1.62	1.52	1.40	1.14	1.13	1.72	1.39	1.62	1.67

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS								
Mass Flow (lb/hr)	A-1 Baseline Rotary Kiln	A-2 Rotary Kiln w/ Oxygen	A-3 Rotary Kiln w/ Wet APC	A-4 Rotary Kiln w/ O ₂ , CO ₂ Ret.	A-5 Rotary Kiln w/ Polymer Stab	A-6 Rotary Kiln w/ Max. Recycle	A-7 Slagging Rotary Kiln	B-1 Pyrolysis	C-1 Plasma Furnace
	Calculated Liquid Water Generation (lb/hr)								
Inputs to Aqueous Waste Treatment System									
Metal Decontamination Water	112.00	112.00	112.00	112.00	112.00	112.00	112.00	112.00	112.00
Lead Recovery Blast Water	29.70	29.70	29.70	29.70	29.70	29.70	29.70	29.70	29.70
Aqueous Waste	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
Rinse Water from 2nd Slab.	403.25	298.25	97.55	469.07	411.32	396.95	556.28	138.38	190.55
Scrubber Water	13,323.00	9,823.00	3,133.00	15,630.00	13,592.00	13,224.00	18,424.00	4,494.00	6,233.00
Total Input to Aqueous Treatment System (available for recycle)	13,947.95	10,342.95	3,452.25	16,320.77	14,225.02	13,842.65	19,201.98	4,854.08	6,645.25
Water Requirements									
Water Input to MTT	482.00	1,824.00	526.00	1.00	663.00	485.00	0.00	0.00	0.00
1st and 2nd Quench Water	10,221.00	4,890.00	0.00	14,360.00	10,354.00	10,224.00	15,425.00	1,411.00	3,549.00
1st and 2nd Scrubber Water	2,259.00	2,259.00	2,259.00	0.00	2,259.00	2,259.00	2,259.00	2,259.00	2,259.00
Rinse Water for 2nd Slab.	403.25	298.25	97.55	469.07	411.32	396.95	556.28	138.38	190.55
Metal Decontamination Water	112.00	112.00	112.00	112.00	112.00	112.00	112.00	112.00	112.00
Mercury Amalgamation Water	29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00
Lead Recovery, Blast and APC	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00
Total Water Requirements	13,549.25	9,455.25	3,066.55	15,014.07	13,871.32	13,548.95	18,424.28	3,992.38	6,182.55
Net Water Generation Rate (recycle - required)	399	888	386	1,307	354	294	778	862	463

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
	WASTE INPUT									
MAIN THERMAL TREATMENT SUBSYSTEM (MTT)										
Combustible	660.4	660.4	660.4	660.4	660.4	660.4	660.4	660.4	50.7	50.7
Noncombustible	1,339.6	1,339.6				1,339.6		1,339.6		
Metal	149	149				617				
Aqueous Liquid									16	16
THERMAL DESORBER										
Combustible									609.7	609.7
Noncombustible				1,339.6					1,340	1,340
VITRIFIER										
Combustible										
Noncombustible			1,340		1,340		1,340			
Subtotal - MTT	2,149	2,149	2,000	2,000	2,000	2,617	2,000	2,000	2,016	2,016
AUXILIARY SUBSYSTEMS										
Metallic Waste (Surface Contamination)	468	468	468	468	468	0	468	468	468	468
Metallic Waste (Entrained Contamination)			149	149	149		149	149	149	149
Mercury	50	50	50	50	50	50	50	50	50	50
Lead Metal	26	26	26	26	26	26	26	26	26	26
Aqueous Waste	80	80	80	80	80	80	80	80	64	64
Special Waste	153	153	153	153	153	153	153	153	153	153
Halide and Sulfide Salts	1	1	1	1	1	1	1	1	1	1
Subtotal - Auxiliary	778	778	927	927	927	310	927	927	911	911
Contaminated Soil (Can replace Soil, below)										
TOTAL WASTE INPUT	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
	PROCESS INPUTS									
MAIN THERMAL TREATMENT SUBSYSTEM (MTT)										
H2O		60	142	910			446			3,033
CH4				1						
O2	1,225		142			79		1,414		355
Air				7,766	6,120					
Air Inleakage			224	2,695						
Soil	482	484		54		524		498		
VITRIFIER										
Soil			499		500		498			
Water				10						
CH4				2						
O2			23	21	15		118			
Air				2						
SCC										
CH4	36		1	427	24		27	80		
O2	174		988							
Air			1982	8,858	496		559	1,662		
WATER										
Primary Quench	1732	1189	4225	10407	2114			2293		
Secondary Quench	427		393		659		751			
Primary Scrubber		2,259		1,864	4	467	1,765	2,254	902	
Secondary Scrubber					494		494			
OTHER										
NaOH		78		64	17	16	78	77	31	31
Na2CO3					121					
CaO	173		158			48				
Electrolyte(Water & CoSO4)									1,036	
Input to Indirect Heater										
Air to Catalytic Oxidizer		10,254				10,429	6,000		2,960	196
CH4				46			155		59	59
Air				948			3,215		1,224	1,224
Subtotal - MTT	4,249	14,324	8,777	34,074	10,664	11,563	14,106	8,278	6,212	4,898
AUXILIARY SUBSYSTEMS										
METAL MELTING (MM)										
Air	0	0	25	25	25	0	25	25	25	25
Water	0	0	19	19	19	0	19	19	19	19
Soil + Flux	0	0	10	10	10	0	10	10	10	10
Subtotal - MM	0	0	54	54	54	0	54	54	54	54

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
LEAD RECOVERY (PbR)										
APC Water (use recycle)	14	14	14	14	14	14	14	14	14	14
Fuel										
Air	21	21	21	21	21	21	21	21	21	21
Blast Water	29	29	29	29	29	29	29	29	29	29
Soil	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Subtotal - PbR	64.26	64.26	64.26	64.26	64.26	64.26	64.26	64.26	64.26	64.26
AQUEOUS WASTE TREATMENT (AQ)										
Resins & Activated Carbon	167.1	181.44	438.6	816.54	228.12	37.14	187.44	337.02	59.94	209.7
Additives (0.051 lb/lb input)	0	0	0	0	0	0	0	0	0	0
Rinse Water for 2° Stabilization	81.32	88.49	217.07	406.04	111.83	16.34	91.49	166.28	28.18	103.06
Subtotal - AQ	167.1	181.44	438.6	816.54	228.12	37.14	187.44	337.02	59.94	209.7
MERCURY AMALGAMATION (HgA)										
Additives (0.1 lb/lb)	5	5	5	5	5	5	5	5	5	5
Nitrogen (0.22 lb/lb)	11	11	11	11	11	11	11	11	11	11
Air (0.60 lb/lb)	30	30	30	30	30	30	30	30	30	30
Water (0.58 lb/lb)	29	29	29	29	29	29	29	29	29	29
Subtotal - HgA	76	76	76	76	76	76	76	76	76	76
TOTAL PROCESS INPUTS	4,555	14,645	9,409	35,084	10,985	11,739	14,487	8,808	6,465	5,301
	INTERNAL SYSTEM RECYCLE									
Scrubber Liquor from Scrubber to Aqueous Waste Treatment	2,705	2,944	7,230	13,529	3,722	539	3,044	5,537	935	3,431
Sludge from Pb Recovery to Aqueous Waste Treatment	0	0	0	0	0	0	0	0	0	0
Resins from Aqueous Waste Treatment to Thermal Treatment	170	184	446	830	232	38	191	343	61	213
Hg Amalgamation Solids to Thermal Treatment	18	18	18	18	18	18	18	18	18	18
Water from Metal Decontamination to Recycle	112	112	112	112	112	0	112	112	112	112
TOTAL INTERNAL SYSTEM RECYCLE (Not including recycle to thermal treatment)	2,817	3,056	7,342	13,641	3,834	539	3,156	5,649	1,047	3,543
TOTAL INPUT	10,300	20,628	19,678	51,652	17,747	15,206	20,570	17,385	10,440	11,771

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
	SYSTEM OUTPUT									
	MAIN THERMAL TREATMENT (MTT) SUBSYSTEM OUTPUT									
SOLIDS										
Slag	1,450	1,452	1,496	161	1,500	1,572	1,493	1,494		
Debris				1,051					1,550	1,550
Nonvitrified Ash										
Metal	170	170				613				
Trace Metals	4	4	4	1	4	4	4	4	1	1
Na2CO3					40					
NaCl/NaF					87					
HCl (50% in Water)										
CaO	116		102							
CaCl2, CaSO4	113		113							
Subtotal - Solids	1,853	1,626	1,716	1,213	1,631	2,189	1,497	1,498	1,551	1,551
	Main Thermal Treatment APC									
LIQUIDS & DISSOLVED GASES										
Scrubber Water	2,705	2,831	7,230	13,436	3,697	516	2,931	5,424	890	3,386
Dissolved Salts		113		93	25	23	113	113	45	45
Dissolved Gases										
O2	5		1	2				1		1
N2			10	13	4		1	3		
CO2		16		23	11	1	8	41	14	30
SO2					1		1	1		
Electrolyte(Water & CoSO4)									1,036	
Subtotal - Liquids & Dissolved Gases	2,710	2,960	7,241	13,567	3,738	540	3,054	5,583	1,985	3,462
GASES										
O2	54	1,194	16	1,622	276	1,215	359	317	375	85
N2	1	7,865	163	14,809	5,071	8,000	5,030	1,272	2,270	150
CO2	1,352	1,237	1,244	2,351	1,330	1,351	1,306	1,402	308	292
H2O Vapor	429	1,587	399	1,484	515	883	1,486	204	453	87
SO2		3		1	2	3	2	2		
Subtotal - Gases	1,836	11,886	1,822	20,267	7,194	11,462	8,183	3,197	3,406	614
INDIRECT-FIRED EXHAUST										
O2				38			130		49	49
N2				728			2467		939	939
CO2				125			425		162	162
H2O Vapor				103			348		133	133
Subtotal - Indirect-Fired Exhaust	0	0	0	994	0	0	3370	0	1283	1283
TOTAL - MTT Subsystems Output	6,399	16,472	10,778	36,041	12,563	14,181	16,104	10,278	6,225	6,910

Table B-1. (continued).

TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS										
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
AUXILIARY SUBSYSTEM OUTPUTS										
Metal Decontamination (MD)										
Clean Metal	463	463	463	463	463	0	463	463	463	463
Grit	5	5	5	5	5	0	5	5	5	5
Water	112	112	112	112	112	0	112	112	112	112
Subtotal - Metal Decon	680	680	680	680	680	0	680	680	680	680
Metal Melting										
Clean Metal	0	0	134	134	134	0	134	134	134	134
Treated Offgas	0	0	46	46	46	0	46	46	46	46
Slag	0	0	23	23	23	0	23	23	23	23
Subtotal - Metal Melting	0	0	203	203	203	0	203	203	203	203
Lead Recovery										
Clean Lead	20	20	20	20	20	20	20	20	20	20
Offgas	35	35	35	35	35	35	35	35	35	35
Water	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
Sludge	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Lead Ingots	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Slag	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Subtotal - Lead Recovery	90.28	90.28	90.28	90.28	90.28	90.28	90.28	90.28	90.28	90.28
Primary Stabilization										
Offgas				34						
Subtotal - Primary Stab.	0	0	0	34	0	0	0	0	0	0
Aqueous Waste Treatment										
Treated Water (0.977 lb/lb aqueous waste, 0.899 lb/lb scrubber liquor)	2,509.96	2,724.82	6,577.93	12,240.73	3,424.24	562.72	2,814.72	5,055.92	903.09	3,147.00
Resins, Organics, Spent Carbon (0.061 lb/lb aqueous waste, 0.061 lb/lb scrubber liquor)	169.885	184.464	445.91	830.149	231.922	37.759	190.564	342.637	60.939	213.195
Treated Offgas (0.007 lb/lb aqueous waste)	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.448	0.448
Concentrated Liquids (0.007 lb/lb aqueous waste, 0.10 lb/lb scrubber liquor)	271.06	181.96	723.56	1,260.46	347.76	31.46	191.96	441.26	48.95	298.55
Salts from Concentrated Liquids	0.00	113.00	0.00	93.00	25.00	23.00	113.00	113.00	45.00	45.00
Rinse Water from 2nd Stab.	81.32	88.49	217.07	406.04	111.83	16.34	91.49	166.28	28.18	103.06
Subtotal - Aqueous Waste Treatment	2,951.46	3,204.80	7,747.96	14,424.90	4,029.48	655.50	3,310.80	5,953.38	1,058.43	3,704.19

Table B-1. (continued).

TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS										
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
Mercury Amalgamation										
Amalgamated Waste (0.21 lb/lb Input)	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Offgas (1.94 lb/lb Input)	97	97	97	97	97	97	97	97	97	97
Contaminated Solids (0.35 lb/lb Input)	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
Subtotal - Mercury Amalgamation	125	125	125	125	125	125	125	125	125	125
Special Waste	153	153	153	153	153	153	153	153	153	153
SUBTOTAL - Auxiliary Subsystem Outputs	3,899.74	4,153.08	8,899.24	15,610.43	5,180.78	1,023.78	4,462.08	7,104.66	2,209.71	4,855.47
SUBTOTAL - Offgas	1,968.56	12,018.56	2,000.56	20,479.81	7,372.56	11,584.56	8,361.56	3,375.56	3,584.45	782.45
TOTAL OUTPUT	10,298.74	20,626.08	19,677.24	51,651.43	17,743.76	16,204.78	20,566.08	17,382.66	10,434.71	11,765.47
MASS BALANCE (Input - Output)	0.92	2.92	0.92	0.92	2.92	0.92	3.92	1.92	4.79	5.79
Volume Reduction Ratio Calculation										
Densities (lb/ft3)										
Input Waste	64	64	64	64	64	64	64	64	64	64
Soil	67	67	67	67	67	67	67	67	67	67
Metal (Input)	26	26	26	26	26	26	26	26	26	26
Metal (Output)	480	480	480	480	480	480	480	480	480	480
Aqueous Liquid	62	62	62	62	62	62	62	62	62	62
Slag	187	187	187	187	187	187	187	187	187	187
Polymerized Salt	80	80	80	80	80	80	80	80	80	80
Polymerized Ash/Metal/Salt	94	94	94	94	94	94	94	94	94	94
Polymerized Lime	96.5	96.5	96.5	96.5	96.5	96.5	96.5	96.5	96.5	96.5
Grouted Debris	126.6	126.6	126.6	126.6	126.6	126.6	126.6	126.6	126.6	126.6
Stab Hg Amalgam	732.96	732.96	732.96	732.96	732.96	732.96	732.96	732.96	732.96	732.96
Volume Solids In (ft3/hr)	45.73	45.73	45.73	45.73	45.73	45.73	45.73	45.73	45.73	45.73
Mass Slag Out (lb/hr)	1,450.78	1,452.78	1,519.78	184.78	1,523.78	1,572.78	1,516.78	1,517.78	23.78	23.78
Mass Nonvitrified Ash Out	0	0	0	0	0	0	0	0	0	0
Mass Special Waste (not stab)	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00
Mass Residues from MD	5.00	5.00	5.00	5.00	5.00	0.00	5.00	5.00	5.00	5.00
Mass MTT Debris & PbR Sludge Out (lb/hr)	0.30	0.30	0.30	1,051.30	0.30	0.30	0.30	0.30	1,550.30	1,550.30
Mass Metal/Pb Out (lb/hr, clean)	657.50	657.50	621.50	621.50	621.50	637.50	621.50	621.50	621.50	621.50
Mass Salts Out (lb/hr)	118.00	118.00	118.00	95.00	157.00	28.00	118.00	118.00	129.00	47.00
Mass Lime Out (lb/hr)	116	0	102	0	0	0	0	0	0	0
Mass Stab Hg Amalgam Out	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
Volume Slag Out (ft3/hr)	7.76	7.77	8.13	0.99	8.15	8.41	8.11	8.12	0.13	0.13
Vol Stab Nonvitrified Ash Out (ft3/hr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Volume Special Wastes (not stabilized)(ft3/hr)	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Vol Stab MD Residues Out (ft3/hr)	0.11	0.11	0.11	0.11	0.11	0.00	0.11	0.11	0.11	0.11
Volume Stab MTT Debris & PbR Sludge Out (ft3/hr)	0.01	0.01	0.01	24.91	0.01	0.01	0.01	0.01	36.74	36.74
Volume Metal/Pb Out (ft3/hr)	1.37	1.37	1.29	1.29	1.29	1.33	1.29	1.29	1.29	1.29
Volume Stabilized Salts Out (ft3/hr)	2.45	2.95	2.45	2.38	3.93	0.70	2.95	2.95	3.23	1.18
Volume Stabilized Lime Out (ft3/hr)	2.40	0.00	2.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vol Stab Hg Amalgam Out	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Volume Solids Out to Disposal (ft3/hr) (Includes 1:1 polymer:ash, 1:1 polymer:salt, 2:1 grout:debris)	15.1	13.2	15.2	30.8	14.6	11.5	13.6	13.6	42.6	40.6
Volume Metal to Recycle (ft3/hr)	1.37	1.37	1.29	1.29	1.29	1.33	1.29	1.29	1.29	1.29
Waste Volume Reduction Ratio (In/Out)	3.02	3.45	3.01	1.49	3.13	3.97	3.37	3.37	1.07	1.13
Mass Processed Waste Out (lb/hr)										
Slag	1450.78	1452.78	1519.78	184.78	1523.78	1572.78	1516.78	1517.78	23.78	23.78
Stabilized Ash (1:1 polymer:ash)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Special Waste	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00	153.00
Stabilized MD Residue (1:1 polymer:residue)	10.00	10.00	10.00	10.00	10.00	0.00	10.00	10.00	10.00	10.00
Stabilized Debris & PbR Sludge (2:1 grout:debris)	0.90	0.90	0.90	3153.90	0.90	0.90	0.90	0.90	4650.90	4650.90
Stabilized Salts (1:1 polymer:salt)	236.00	236.00	236.00	190.00	314.00	56.00	236.00	236.00	258.00	94.00
Stabilized Lime (1:1 polymer:lime)	232.00	0.00	204.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hg Amalgam	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50
Total Mass Processed Wastes Out (lb/hr)	2093.18	1863.18	2134.18	3702.18	2012.18	1793.18	1927.18	1928.18	5106.18	4942.18
Waste Mass Reduction Ratio (In/Out)	1.40	1.67	1.37	0.79	1.45	1.63	1.62	1.62	0.67	0.68

Table B-1. (continued).

	TABLE B-1 OVERALL MASS BALANCES FOR NINETEEN ITTS SYSTEMS									
Mass Flow (lb/hr)	C-2 Plasma w/ CO2 Retent.	C-3 Plasma w/ Steam Gas.	D-1 Fixed Hearth Pyro CO2 Ret	E-1 Thermal Desorption	F-1 Molten Salt Oxidation	G-1 Molten Metal	H-1 Steam Gasification	J-1 Joule-Heated Vitrification	K-1 Desorption w/ MEO	L-1 Desorption w/ SCWO
	Calculated Liquid Water Generation (lb/hr)									
Inputs to Aqueous Waste Treatment System										
Metal Decontamination Water	112.00	112.00	112.00	112.00	112.00	0.00	112.00	112.00	112.00	112.00
Lead Recovery Blast Water	29.70	29.70	29.70	29.70	29.70	29.70	29.70	29.70	29.70	29.70
Aqueous Waste	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	64.00	64.00
Rinse Water from 2nd Stab.	81.32	88.49	217.07	406.04	111.83	16.34	91.49	166.28	28.18	103.06
Scrubber Water	2,705.00	2,831.00	7,230.00	13,436.00	3,697.00	516.00	2,931.00	5,424.00	890.00	3,386.00
Total Input to Aqueous Treatment System (available for recycle)	3,008.02	3,141.19	7,668.77	14,063.74	4,030.53	642.04	3,244.19	5,811.98	1,123.88	3,694.76
Water Requirements										
Water Input to MTT	0.00	60.00	142.00	910.00	0.00	0.00	446.00	0.00	0.00	3,033.00
1st and 2nd Quench Water	2,159.00	1,189.00	4,618.00	10,407.00	2,773.00	0.00	751.00	2,293.00	0.00	0.00
1st and 2nd Scrubber Water	0.00	2,259.00	0.00	1,864.00	498.00	467.00	2,259.00	2,254.00	902.00	0.00
Rinse Water for 2nd Stab.	81.32	88.49	217.07	406.04	111.83	16.34	91.49	166.28	28.18	103.06
Metal Decontamination Water	112.00	112.00	112.00	112.00	112.00	0.00	112.00	112.00	112.00	112.00
Mercury Amalgamation Water	29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00	29.00
Lead Recovery, Blast and APC	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00	43.00
Total Water Requirements	2,424.32	3,780.49	5,161.07	13,771.04	3,566.83	555.34	3,731.49	4,897.28	1,114.18	3,320.06
Net Water Generation Rate (recycle - required)	584	-639	2,508	293	464	87	-487	915	10	375

Metal Decontamination Subsystem

This subsystem is designed to accommodate metallic wastes with surface contamination (usually empty bins or drums). The metal is sand- or water-blasted to remove the radioactivity and then certified for shipment and reuse. The input to this subsystem is 468 lb/hr. One primary treatment subsystem (G-1) is a molten metal process that accepts surface-contaminated metallic waste and uses fluxing agents to separate the metal from the radioactive constituents.

Lead Recovery Subsystem

The lead recovery subsystem is described in the Phase 1 report.² It consists of a water blaster, a lead melter, a vitrifier, air pollution control system, and other related equipment. The subsystem treats lead with surface contamination that can be recycled after decontamination. The assumed feed rate is 26 lb/hr of surface-contaminated lead. The system also requires water input (26.8 lb/hr) and fuel, air, and quench water (flow rates unspecified in the Phase 1 report).

Aqueous Waste Treatment Subsystem

The aqueous waste treatment subsystem is intended to treat aqueous wastes that are part of the input to the nineteen systems as well as the scrubber liquor (salt solution from the gas scrubber). The aqueous wastes amount to 80 lb/hr. Additives (about 4 lb/hr) are also required. Two primary treatment subsystems (K-1 and L-1) treat 16 lb/hr of the aqueous waste, resulting in 64 lb/hr to be treated by the aqueous waste treatment subsystems.

Special Waste Treatment Subsystem

Special wastes are those that are treated separately because of their inability to be grouped with any of the other MLLW. These wastes amount to 153 lb/hr. Details of this subsystem are still being developed.

Mercury Amalgamation Subsystem

The mercury amalgamation subsystem treats elemental mercury contained in the waste stream. It accepts 50 lb/hr of mercury, and requires 5 lb/hr of additives, 11 lb/hr of nitrogen, 30 lb/hr of air, and 29 lb/hr of water.

Aqueous Stream Balances

In addition to the overall mass balance performed on the input and output streams for the nineteen systems, a balance was also performed on the amount of water required by each of the systems and the amount of water available for recycle within each system. The intent was to use as much of the recycle water as possible within the systems; no discharge of liquid water from any of the systems was planned.

Water requirements for each system include scrubber water, quench water, water input to the primary thermal treatment subsystem, and minor amounts of water required by the various subsystems. Aqueous streams that are routed to the aqueous waste treatment include aqueous waste input to the system and output from the various subsystems (the largest component being the primary subsystem output, which includes scrubber water, quench water, and water input directly to the primary treatment system).

For most of the systems, as presently configured, an excess of water is generated (that is, the amount of water available for recycle from the aqueous waste treatment subsystem exceeds the water requirement). The source of this water is the condensation of water vapor that results from the combustion of natural gas (used for heating purposes) and hydrogen-bearing waste constituents. Only two systems (C-3 and H-1) require water input in addition to that available in the recycle (both of these systems employ gasification and require water for this purpose).

Excess water generated by the systems can be processed in several ways to avoid discharge of liquid effluent. One way to manage the excess water would be to evaporate it. Evaporation could be achieved within the aqueous waste treatment subsystem itself or within the scrubber in the primary treatment subsystem.

The aqueous waste treatment subsystem includes, among other processes, a concentrator wherein water is evaporated from sludge. This water vapor is then condensed and recycled to the system. By not condensing the entire water vapor stream, some of the water vapor could be discharged from the system.

Another method that could be used to evaporate water would be to operate the gas scrubber in the primary treatment subsystem at higher temperature. The operating temperature of 120°F results in most of the scrubber water being condensed and routed to the aqueous waste treatment subsystem. ASPEN calculations were performed for several of the systems to determine the scrubber operating temperature that would allow for sufficient evaporation. For System A-1, a scrubber temperature of 128°F would allow for an additional 399 lb of water to leave the system in the gas phase. For System A-2, a scrubber temperature of 158°F would be required to evaporate an additional 888 lb of water.

REFERENCES

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