SUMMARY REPORT

INTEGRATED

PROCESS ANALYSES STUDIES

ON

MIXED LOW LEVEL AND

TRANSURANIC WASTES

Office of Science and Technology
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EXECUTIVE SUMMARY

Options for integrated thermal and nonthermal treatment systems for mixed low-level waste (MLLW¹) are compared such as total life cycle cost (TLCC), cost sensitivities, risk, energy requirements, final waste volume, and aqueous and gaseous effluents. The comparisons were derived by requiring all conceptual systems to treat the same composition of waste with the same operating efficiency. Thus, results can be used as a general guideline for the selection of treatment and disposal concepts. However, specific applications of individual systems will require further analysis. The potential for cost saving options and the research and development opportunities are summarized. Background and a summary of results are included in this executive summary.

Background

From 1993 to the present, the Department of Energy (DOE) Office of Science and Technology (OST), sponsored a series of systems engineering analyses to guide its future research and development (R&D) programs for the treatment of existing DOE MLLW. OST called this effort the Integrated Process Analysis (IPA) program. The technologies were evaluated as part of a total treatment system capable of processing the MLLW to meet the U.S. Environmental Protection Agency's (EPA) Land Disposal Restrictions (LDR) for MLLW. The first study, Integrated Thermal Treatment Systems (ITTS) — Phase 1, looked at relatively mature thermal treatment technologies (Reference 7). After completion of the first phase, the ITTS study was extended to Phase 2 to consider more innovative and developmental thermal treatment technologies (Reference 6).

The ITTS studies were guided by a technical support group (TSG) consisting of representatives from several DOE field offices and laboratories, as well as consulting engineers involved in the private sector hazardous waste treatment industry. The TSG also included one non-technical person who had been involved in a variety of DOE oversight activities for the State of Colorado. This individual provided the ITTS study members "public insight" for the evaluation of the technologies.

As a result of an internal peer review (Reference 19) of Phases 1 and 2 of the ITTS study, a similar examination of nonthermal treatment systems, known as the Integrated Nonthermal Treatment Systems (INTS) study (Reference 1), was conducted. In the INTS study, nonthermal treatment systems were defined as those systems that process wastes at temperatures less than 350° C. This temperature was chosen to minimize volatilization of heavy metals and radionuclides and formation of dioxins and furans in the offgas or air pollution control (APC) subsystem.

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¹MLLW contains both hazardous constituents as defined under Resource Conservation and Recovery Act (RCRA) and radioactive materials regulated under the Atomic Energy Act.

Because of the growing importance of stakeholder involvement in DOE decision making, as well as recommendations from the internal peer review (Reference 19), public involvement in the INTS study was established through a working group of 20 tribal and stakeholder representatives (Native Americans, state and local government representatives, citizens, environmental groups, and personnel from private companies). This Tribal and Stakeholder Working Group (TSWG) was organized to provide perspectives on the formulation of the INTS study, to provide comments on the process and results of the INTS and ITTS studies, and to identify principles against which the treatment systems should be designed and evaluated. The TSWG developed a set of principles reflecting their concerns, namely: (1) minimize effluents; (2) minimize effect on human health and the environment; (3) minimize waste generation; (4) address social, cultural, and spiritual considerations (e.g., land use); (5) provide accurate and timely information; and (6) involve stakeholders in the DOE procurement process when DOE contemplates application of treatment technologies on DOE wastes. These principles were compared to the technical criteria used in the ITTS and found to be generally consistent.

The TSWG principles, as well as other performance measures, were used to make a detailed comparison of thermal and nonthermal treatment systems. Relative risk factors, such as worker safety and public health, were also evaluated and compared for several thermal and nonthermal systems. These comparisons were presented to the TSWG in several meetings. Based on the TSWG's suggestion, one of the nonthermal systems was selected for comparison of performance and cost by replacing nonthermal grout stabilization with vitrification. This resulted in the Enhanced Nonthermal Treatment Systems (ENTS) study (Reference 2) in which five enhanced nonthermal systems were evaluated that included hybrid systems consisting of nonthermal primary treatment and thermal metal recovery and waste stabilization technologies. The ENTS study also investigated the cost impact of replacing grout with improved nonthermal stabilization materials and increasing the reaction rate of the organic waste treatment process.

In all, thirty systems were conceptually designed to treat alpha-contaminated MLLW, to produce waste forms in compliance with Resource Conservation and Recovery Act (RCRA), and to meet current DOE requirements for disposal. These systems were designed to process the same mixture of MLLW at 2,927 pounds per hour in a single, centralized facility operating for 40 weeks/year at 60% availability (i.e., 4,032 hours/year or 46% operation during a year). A basis of 3.7 million cubic feet (105,000 cubic meters) was used as the treatable inventory. If the bulk density of the MLLW is 64 lb/ft³, the inventory basis of these studies was approximately 236 million pounds which could be treated in 20 years or approximately 70% of the currently estimated MLLW inventory plus 5 years of projected generation.

In 1993, the DOE inventory of MLLW from all DOE sites (Reference 21) was used as the starting point for the ITTS Phase 1 study. From this inventory, an average waste profile

was developed (Reference 9). The waste profile consisted of a wide range of combustible and noncombustible materials such as paper, plastics, metals, concrete, soils, sludges, etc. contaminated with trace quantities of radioactive materials (including alpha) and RCRA regulated wastes. This same waste profile was used through all the subsequent studies to allow a consistent comparison of systems even though estimates of the inventory volume and content have changed as improved estimates have been developed by the DOE sites (Reference 22). Mass material balance flowsheets were developed to determine the amount of effluents from each system.

Discussion of Results

Up to \$1 to \$2 billion (out of a range of TLCCs of \$2.1 to \$3.9 billion) can be saved during treatment of legacy waste and future MLLW by selecting and using systems that: (1) offer high reliability and operating efficiency, (2) minimize disposal volume, (3) minimize the generation of new (secondary) waste, (4) increase safety and health through more stable waste forms that also have a low volume and low disposal cost, and (5) increase the likely regulatory and stakeholder acceptability, e.g., by addressing tribal and stakeholder principles (see Section 2.0).

Total Life Cycle Costs (TLCC) are significantly affected by: (1) operating and maintenance efficiency (~50-60% of TLCC); (2) efficiency in characterization, sorting, and preparation (~25-30% of TLCC); and (3) costs of disposal (~10-20% of TLCC). Thus, significant incentives exist to focus development activities on these areas to reduce costs. About \$370 million in savings can be realized by improving the overall system availability from the assumed bases of 4,032 hours (46%) on line per year to at least 5,850 hours per year (67% on line). About \$430 million in additional savings can be achieved by reducing up-front waste characterization and sorting costs by 50%. Savings can be achieved if the final volume of waste is reduced and is realized not only by the savings in disposal cost but also by savings in the certification and handling of fewer waste packages. Waste volume reductions can be achieved by choosing a low volume waste form (e.g., vitrified, ceramic, or phosphate cement forms which increase the amount of waste included in a unit volume of waste form).

Within the accuracy of the TLCC estimates, little difference was estimated among the treatment TLCC using different thermal treatment technologies. Likewise, little difference in TLCC was estimated among the different technologies for non-thermal treatment. However, in general, the non-thermal treatment TLCC was about 40-60% higher than thermal treatment TLCC, roughly \$3.5 billion as compared to \$2.5 billion over 20 years. This is due to greater operation and maintenance (O&M) costs and the larger final waste volumes produced with non-thermal stabilization processes resulting in increased disposal costs. Unit treatment costs range from around \$8/lb for most ITTS systems to more than \$13/lb for catalyzed wet oxidation and acid digestion INTS systems. The thermal system unit cost may be reduced further by approximately a dollar

per pound because, unlike non-thermal systems, thermal systems can use contaminated soil for formulation of the "vitrified" or glass ceramic final waste form. Treatment of soil through non-thermal systems was not considered advisable.

Versatility and flexibility to treat a variety of wastes are dominant attributes to consider for choosing centralized treatment and stabilization operations. Based on the waste profile of the IPA program, about 70% of the incoming waste is treatable by a thermal process; however, only about 20% of the incoming waste is combustible and treatable by nonthermal methods based on the MLLW composition used in this study. The rest of the inorganic waste entering a nonthermal system requires removal of residual organic contaminants prior to stabilization. If this is done by non-thermal processes, about 50% of the incoming waste is treatable. Technologies with wide versatility are the rotary kiln, the plasma arc, and the DC arc melter, while molten metal, molten salt, and steam reforming appear to be less versatile, especially for large-sized waste materials. Those systems in the study having the least versatility are nonthermal chemical oxidation and super-critical water oxidation.

Other cost saving opportunities exist on sites where contaminated soil can be used as the glass former, reducing treatment unit costs (~\$10 per pound before disposal) by about 10%. However, soils may require somewhat higher melting temperatures that only certain immobilization technologies can provide.

The volume of offgases from the nonthermal systems are approximately one-twentieth of the offgases from a rotary kiln with vitrifier, and approximately one-fifth of the offgas from a plasma arc system. Thus, large differences in offgas mass flow can be achieved through selection of different energy sources and methods of treatment, e.g., natural gas heat or electric heat. Although lower offgas mass flows alone do not guarantee a system with lower total pollutant emissions, those with smaller offgas flowrates require smaller and less expensive air pollution control systems even if a highly redundant offgas treatment (air pollution control) subsystem is used to assure minimum emission of pollutants.

Liquid aqueous effluents are produced by most systems; however, steam reforming, molten metal, or grouting of the waste did not produce liquid effluents but rather consumed water. Comparisons of treatment systems are summarized from Reference 17 as follows:

	COMPARISON OF THERMAL AND NON-THERMAL SYSTEMS	
	Thermal Treatment Systems	Non-thermal Treatment Systems
Technical Maturity	Existing or near term technology	Requires considerable development before implementation
Incoming waste treatable	60-90% (Only 20% of waste combustible)	50-70% by using more than one non-thermal technology in the same system
TLCC	Less than non-thermal	More expensive than thermal about \$1-1.5B
Total Capital Cost	15-25% of TLCC	15-25% of TLCC
Unit Op. Cost excluding Disposal	\$8-10/lb	\$12-13/lb
All Maint & Op Receiving & Prep	50-60% of TLCC 25-30% of TLCC	50-60% of TLCC 25-30% of TLCC
APC capital	5% of total capital costs	2% of total capital costs
Secondary Waste from APC	About 30% of the total waste volume for disposal	About 10% of the total waste volume for disposal
Total Disposal Volume	About 30% of incoming waste volume	About 80-90% of incoming volume

	COMPARISON OF THERMAL AND NON-THERMAL SYSTEMS	
Disposal Costs	~ 10% of TLCC	~ 20% of TLCC
Energy Cost	Less than 1% of TLCC	Less than 1% of TLCC
Destruction Efficiency	99.999+	>98% Organic removal from solid matrices may not be complete and extent of removal needs further verification
Offgas Volume	Depends on the mode of heating and is reduced by recycle of gases, using oxygen or avoiding internal fuel addition	Up to 20 times less than from thermal units

The secondary waste (new generation) from the APC subsystem of thermal treatment units will likely result from capture and immobilization of volatile materials. Low temperature immobilization (e.g., polyethylene) was assumed in all studies to contain the materials volatilized from the thermal treatments.

Non-incinerator thermal systems (e.g., steam reforming) will probably (based on conversations with regulators) still be subjected to the same emission standards as thermal treatment units. However, the evidence is comforting that dioxin and furan releases are expected to be much less from non-thermal systems. Any generation of dioxin and furans in off gases is expected to be removed by the more advanced APC subsystem concepts used for this study. Emissions are not expected to be a problem with the more advanced APC subsystems for either thermal or non-thermal treatments.

In general, the relative estimated health risks associated with ITTS and INTS technologies were found to be very similar. The risks to workers are higher than the risks to the public for all systems. The dominant risks for all systems are due to handling, sorting, and shredding, and transportation of hazardous reagents. Thus, careful attention to these operations can reduce worker risks. Primary treatment and disposal (strongly related to the stability of the final waste form) contribute relatively small fractions to the total risk. The treatment technologies with the lowest health risk were those that produced a stable waste form early in the treatment process such as slagging rotary kilns and plasma systems.

Treatment System Options, Sensitivities, and Performance

The capital cost of a high performance air pollution control (APC) subsystem with redundancy is only about 2%-5% of the total life cycle cost. The investment in the APC to provide the additional assurance appears attractive.

One central facility with vitrification rather than five regional facilities producing grout can save \$1.8 billion.

For centralized treatment of MLLW, the TLCC for nonthermal systems is \$1 to 1.5 billion more than thermal systems.

Other than differences between nonthermal and thermal treatment systems, the type of technology makes little difference if operating availability (hours operated per year) are the same for each. Examples of cost sensitivities are:

- A 50% increase in availability (e.g., $\frac{1}{2}$ time to $\frac{3}{4}$ time each year) can save \$400M.
- Operating and Maintenance is the major cost element - a 50% decrease can save \$700M.
- Although later time and motion studies showed smaller time requirements for receiving and preparation than reported in the INTS and ITTS studies, the overall manpower requirements for the total system were shown to be about 30% higher than originally estimated. However, this was within the accuracy of the TLCC estimates.
- Hybrid combinations of thermal and nonthermal treatments (e.g., vitrify nonthermal residues) does not make hybrid nonthermal more competitive with all thermal.

Cost Incentives for Waste Forms

- Because of higher disposal volume, the treatment and disposal costs for a system producing grout are higher than the cost for system producing a high temperature slag or vitrified product assuming equal availability. Vitrification rather than grouting of waste coupled with various thermal treatment technologies can save \$500M to \$1,000M. As the disposal cost per unit volume of waste increases, the amount of cost savings from producing a low-volume of waste increases. Conversely, if disposal costs are low enough, the incentive for using vitrified materials is marginal.

- Phosphate cement waste forms are competitive with glass waste forms on a cost, volume, and waste loading basis.
- Increasing the waste loading in waste forms can save \$750 million (e.g., from 30% to 50% by weight) (Reference 18).
- Vitrification can save disposal costs over grout stabilization because of differences in waste loading and final volume of waste.
- As the cost of disposal increases, for example from \$706/m³ (\$20/ft³) to \$8475/m³ (\$240/ft³), the TLCC at a 30%wt loading increases from about \$2,000M to \$3,000M or by about 25% to treat the legacy MLLW in the DOE system. By increasing the waste loading to values up to 50%wt, the savings are approximately 10% of the cost of disposal.
- Use of phosphate bonded (based) cements (ceramics) as the stabilized waste form is competitive with vitrified and ceramic waste forms. However, more development work is necessary to assure long term integrity of the PBC in a disposal facility.

Cost Incentives for Alternative Equipment Concepts (Replaceable Hearth, Portable Systems)

- Little cost incentive exists for using a replaceable hearth (in-can processing) compared to a centralized melter unless one system is known to have more reliability than another.
- Portable treatment systems can be greater than a factor of 4 more expensive compared to shipment to a central facility for treatment where the facility is designed to treat all the MLLW in the complex. The study included waste scheduled for portable treatment in the DOE site treatment plans (e.g., 8.5 million pounds).

Waste Flow (Impacts of Pre-treatment and Post-treatment Storage, etc.)

The cost impact of storing DOE MLLW for an extended period was also studied. Presently no plans have been made to publish those results. The results of this study were twofold: (1) for every year a potential treatment technology is unavailable, a penalty cost for pre-treatment storage is incurred, and (2) if treated waste cannot be disposed for a set time, a penalty cost for storage is incurred.

- Treating waste in 10 years vs 20 years can save \$80M primarily, in storage costs.

- Prolonged storage can add significantly to the TLCC. The storage study found that the costs for MLLW centralized storage range from \$700 million to \$2.5 billion and \$2,500 per cubic meter to \$11,500 per cubic meter for 25 years of storage.

Future Development Needs

Future development needs were identified as follows:

- (1) Improved operating efficiency particularly in the front-end characterization and preparation of waste to reduce costs.
- (2) The toxic metals/radionuclides partitioning study to assess potential releases to the APC subsystem showed that considerable improvement should be sought throughout the DOE testing program both in terms of the amount of partitioning data acquired in the conduct of the program and the methods for collecting such data.
- (3) Air pollution control systems testing to assure containment:
  - confirm the capability of final polishing carbon filters to stop mercury and dioxins/furans.
  - performance of APC subsystems under reducing and steam reforming conditions need to be better known compared to oxidizing conditions.
  - Performance of continuous emission monitors or continuous process control monitors to allow reduction in the front end characterization requirements.
- (4) Testing of the effectiveness of various waste forms to assure delisting of waste (reduces disposal cost) and assures long term containment of radionuclides in the waste. Effectiveness of increased waste loadings to decrease costs.
- (5) Additional study of the impacts of waste characteristics and analysis on performance to determine the versatility or tolerance of treatment systems and the APC subsystem to various types of waste and the design safety margin that will be needed.

Capsule Summary of Results of Ancillary Studies

During the IPA program, analyses were being performed on the basis of a fixed set of assumptions; however, questions arose regarding the sensitivity of the costs to these assumptions. One study (Reference 8) evaluated the sensitivity of system life cycle costs with respect to cost element and subsystem, facility capacity and availability, operating life, contingency allowance, and disposal costs. A time and motion study (Reference 4) was also performed to estimate the labor required to operate each system and the time required for treatment of a drum of waste for each system. The time and labor required to process a unit of waste highlighted critical path issues and potential bottlenecks in each system.

Portable Treatment Systems (PTS) (Reference 16) were also studied to evaluate the feasibility of using a portable treatment system comprised of several mobile treatment units (MTUs) rather than a fixed central treatment facility. Both the PTS and the central treatment facility were conceptually designed to treat the same profile of contact-handled (non-alpha, while all other IPA studies assumed alpha) MLLW streams. The analysis focused on the MLLW designated by the DOE Site Treatment Plans for treatment by planned or existing portable treatment units (8.5 million pounds). These MLLW streams were compiled into physical matrix sets for existing and projected 5-year inventories that were then used to establish the PTS needed to meet the treatment requirements. The concept was to treat the existing and 5-year projected inventory over 5 years operating 800 hrs/year.

In addition to summarizing the foregoing *major* studies conducted under the IPA program, this report briefly touches on the major findings and conclusions of other related systems studies, as well, which cover various questions that arose during the course of this work. Among the studies summarized in this work are a replaceable hearth, i.e., "in-can" melter, study (Reference 15), a comparative health risk analysis (Reference 12), a toxic metals and radionuclide partitioning study (Reference 11), a waste form R&D study (Reference 13), a "plain language" summary (intended for the general public and stakeholders comparing the major results of the INTS and ITTS and describing in greater detail the stakeholder input process) (Reference 20), and a combined waste management/environmental restoration incineration system study (Reference 3).

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ACRONYMS AND ABBREVIATIONS

Ag	silver
APC	air pollution control
BDAT	best demonstrated available technology
°C	degrees Celsius (or Centigrade)
CEM	continuous emission monitor
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Register
CO	carbon monoxide
CO ₂	carbon dioxide
CWO	catalytic wet oxidation
D&D	Decontamination and Decommissioning
DE	destruction efficiency (for nonthermal systems)
DETOX	Catalytical Chemical Oxidation(Delphi Process)
DOE	U.S. Department of Energy
DOIT	demonstration of innovative technologies
DRE	destruction removal efficiency (for thermal systems)
EH	Office of Environment, Safety and Health (DOE)
EM	Office of Environmental Management (DOE)
EPA	U. S. Environmental Protection Agency
ES&H	environment, safety and health
°F	degrees Fahrenheit
FFCA	Federal Facilities Compliance Act
FTE	full-time equivalent
g	gram or gallon
GAC	granulated activated carbon
GOCO	government-owned, contractor-operated
GPCR	gas phased corona reactor
gpm	gallons per minute
GVW	gross vehicle weight
HCl	hydrochloric acid
HEPA	high-efficiency particulate air (filter)
HLW	high level waste
ID	Idaho
INEEL	Idaho National Engineering and Environmental Laboratory
INTS	Integrated Nonthermal Treatment Systems Study
ITTS	Integrated Thermal Treatment Study
kg	kilogram
l	liter
LANL	Los Alamos National Laboratory
LDR	Land Disposal Restrictions (under RCRA)
LMITCO	Lockheed Martin Idaho Technology Company

ACRONYMS AND ABBREVIATIONS (continued)

LLW	low-level waste
m	meter or micro
MEO	Mediated Electrochemical Oxidation
mg	milligram
MK	Morrison Knudsen Environmental Services, Inc.
MLLW	mixed low-level waste
MMT	molten metal technology
MSO	molten salt oxidation
MTU	mobile treatment unit
MWFA	Mixed Waste Focus Area
MWIR	Mixed Waste Inventory Report
NA	not applicable
NaCl	sodium chloride
NM	New Mexico
O&M	Operation and Maintenance
OR	DOE Operations Office in Oak Ridge
ORNL	Oak Ridge National Laboratory
OST	Office of Science and Technology
PAN	passive/active neutron
PBC	phosphate bonded cement (ceramic)
PCBs	polychlorinated biphenyls
PEIS	programmatic environmental impact statement
PICs	products of incomplete combustion
psia	pounds pressure per square inch absolute
psig	pounds pressure per square inch gauge
PTS	portable treatment system
R&D	research and development
RCRA	Resource Conservation & Recovery Act of 1976
RDDT&E	Research, Development, Demonstration, Testing and Evaluation
RTR	real time radiography
SCC	secondary combustion chamber
SRS	Savannah River Site
SCWO	Supercritical Water Oxidation
TCLP	Toxicity Characteristic Leaching Procedure
TD	thermal desorption
TLCC	Total Life Cycle Cost
TRU	transuranic
TS	toxic substances
TSCA	Toxic Substances Control Act of 1976
TSG	technical support group
TSWG	tribal and stakeholders working group

ACRONYMS AND ABBREVIATIONS (continued)

UTS	universal treatment standards
UV	ultraviolet
VOCs	volatile organic compounds
WGA	Western Governors Association
WM	DOE's Office of Waste Management (EM-30)
WPC	water pollution control
WPI	Waste Policy Institute

SECTION 1.0

BACKGROUND

In 1993, the Office of Science and Technology (OST) of the Office of Environmental Management (EM) of the U.S. Department of Energy (DOE) commissioned a series of integrated systems engineering studies. The studies uniformly compared widely varying thermal treatment technologies designed to treat DOE Mixed Low-Level Waste (MLLW). The first two studies dealt with traditional thermal systems and incinerators and more advanced and innovative thermal treatments. These studies were called Phase 1 (ten technologies) and Phase 2 (nine technologies) of the Integrated Thermal Treatment Systems (ITTS) study, respectively. As an addendum to the Phase 2 study, a twentieth system using a rotary kiln and grout final stabilization was added to represent a system using totally off-the-shelf technology.

Subsequently, OST conducted a similar study, examining nonthermal technologies crafted into five integrated systems. This Integrated Nonthermal Treatment Systems (INTS) study contained the same basic assumptions and theoretical waste input as the thermal study. The alternatives considered were innovative treatments for organic liquids and sludges, process residues, soils, and debris. Organic destruction methods included mediated electrochemical oxidation, catalytic wet oxidation, and acid digestion. Other variations in the study examined stabilization technologies and mercury separation methods for the treatment residues.

The major difference between the ITTS and the INTS was that in the latter, a working group of tribal and stakeholder representatives provided information to the technical team so that public perceptions and concerns were more widely integrated into the study process and into the systems studied. Since completion of the INTS, additional systems studies have been conducted on enhanced nonthermal systems (using nonthermal treatment as primary treatment but thermal treatment for metals recovery and waste stabilization), a portable treatment system, a replaceable hearth melter, an ITTS/INTS comparison, comparative health risks of selected systems from the INTS and ITTS studies, toxic metals and radionuclide partitioning, two combined waste management/ environmental restoration incineration systems, systems time and motion, cost impact sensitivities, and waste storage cost impacts.

In the thermal studies, all subsystems, including facilities, equipment, and methods needed for integration of each of the thermal systems were identified. Typical subsystems needed for complete thermal treatment of MLLW are incoming waste receiving and preparation (characterization, sorting, sizing, and separation), primary and secondary (if needed) thermal treatment, air pollution control, primary and secondary stabilization, metal decontamination, metal melting, mercury recovery, lead recovery, special waste, and aqueous waste treatment.

As part of the preconceptual design process, functional and operational requirements, flow sheets and mass balances, and conceptual equipment layouts were developed for each system. The components estimated to be required were technology development, production facility construction, pre-operation, operation and maintenance, and decontamination and decommissioning. Preconceptual design data and other technology information gathered during

the study were examined and areas requiring further development, testing, and evaluation were identified and recommended. Performance was measured by calculating offgas and water effluents out the stack. Total Life Cycle Costs (TLCC) of operating the system for 20 years and disposing of all its residual wastes were developed. As requested by the Mixed Waste Integrated Program and its successor, the Mixed Waste Focus Area, the systems were not rank ordered.

DOE MLLW consists of organic and inorganic solids, sludges, and liquids comprising a wide variety of materials contaminated with radioactive substances. Treatment is needed that will destroy the organic material leaving only a stabilized residue for disposition.

Since many DOE sites have different types of MLLW, rather than trying to analyze systems designed to treat each specific waste stream, generic systems to treat a hypothetical composite waste stream were developed. Thermal treatment, or the best demonstrated available technology (BDAT), has been determined by the U.S. Environmental Protection Agency (EPA) to be the most effective method for treating the organic waste constituents typically found in MLLW.

Phase 1 of the ITTS focused on establishing a baseline understanding of well-developed thermal treatment technologies, namely a rotary kiln incinerator with six variations, a fixed hearth controlled-air incinerator, an indirectly fired pyrolyzer, a thermal desorber for inorganic residue with a rotary kiln for the combustible waste fraction, and a plasma hearth melter system. The variations were used to examine the effects of combustion gas, air pollution control system design, and stabilization technology for the treatment residues on system performance and costs. Phase 2 of the ITTS focused on innovative technologies such as one-step processing, degasification, low-temperature oxidation, molten salt oxidation (MSO), molten metal destruction, mediated electrochemical oxidation (MEO), and supercritical water oxidation (SWO).

Phase 1 initially considered ten treatment systems that included various combinations of the incinerator, air pollution control, and waste stabilization subsystems. Incinerator subsystems considered were the rotary kiln, plasma arc furnace, and fixed hearth furnace. Air pollution control (APC) subsystem designs included both wet and dry technologies. The baseline APC system was designed to assure performance that would exceed current EPA regulations for emissions control by an order of magnitude.

Waste stabilization subsystems considered were concrete, polymer, and glass- or vitrified soil-based waste forms. Hazardous wastes were stabilized to afford not only compliance with federal law but also to assure long-term isolation of hazardous materials. Mercury, a specialty waste, was amalgamated, and metals (including bulk lead) were removed and recycled after treatment. Many options could have been considered; however, due to time and resource constraints a group of DOE scientific and engineering experts reduced the number of primary treatment options in phase one of the ITTS study to ten. The experts also preserved options to evaluate different parameters such as incinerator types, oxygen-versus-air for the combustion gas, carbon dioxide retention, and wet versus dry/wet air pollution control configurations.

Functional and operational requirements, flow sheets, mass balances, and conceptual equipment layouts were developed for each system as part of the design process. Mass balances accounted for all materials treated or used in the processes. All secondary residues were processed according to regulatory requirements. Final waste volumes were estimated for transportation and disposal. Disposal cost estimates were applied to the disposal volume of each system as part of the total costs.

The various wastes identified for treatment are described in the DOE Mixed Waste Inventory Report (References 19 and 20), and include both alpha-emitting and non-alpha emitting. All wastes were assumed to be contact-handled, so that triple-containment shielding was not a severe design restraint. While the latter stage of the ITTS Phase 2 and the INTS studies had available to them updated waste inventory information, these new data were purposefully not used to afford legitimate comparisons to be made with ITTS Phase I. The systems evaluated were required to treat all waste stored in the DOE complex. This requirement established the need for several treatment lines to accommodate the range of MLLW encountered.

OST also performed paper studies (discussed in greater detail in Section 5) on ancillary issues to analyze various aspects of MLLW treatment.

The OST replaceable hearth study (Reference 15) explored the performance of an "in-can" melter. The replaceable hearth melting approach is an alternative melting and vitrification alternative to the more traditional hearth melting furnace with tapping and casting of molten products into secondary containers. This approach eliminated all tapping and casting functions and associated equipment and eliminated internal hearth refractory maintenance and replacement considerations for a system to treat MLLW.

The OST also engaged INEEL to conduct a Portable Systems Study (PTS) (Reference 16) to better define the potential role of portable treatment with respect to DOE MLLW, highlight obstacles to implementation, and identify opportunities for future R&D emphasis. The study first established a representative set of MLLW, then formulated portable treatment concepts to meet the required processing needs for treating these wastes. A comparison of a central fixed facility and four portable treatment systems processing the same waste with the same bases showed that the cost of a centralized portable treatment system was about \$14/lb compared with a weighted composite of four individual portable facilities at about \$20/lb. Although the bases of this study were different than all other studies used in the ITTS study and the ancillary ones for further analyses, the results compare with the ITTS studies for a rotary kiln central facility where the unit costs were \$7/lb. In general, no economic incentive exists for a PTS, but non-economic factors at a particular site may be influential in the choice of treatments. Further, no significant technical obstacles were identified to design and implement equipment to treat MLLW in either the PTS or a centralized facility.

An "enhanced" nonthermal study was conducted to explore hybrid systems using promising subsystems of thermal and nonthermal units. Detailed comparisons of various system parameters

are presented in Reference 2. System NT-5, catalytic wet oxidation (CWO) from the INTS study, was chosen as the basis for the enhanced nonthermal study because CWO can treat combustible debris, remove it from the waste stream, and decrease the stabilized waste volume.

The enhanced study found that the capital costs for each of the five enhanced systems were higher than both the thermal and nonthermal systems, while operation and maintenance (O&M) costs were roughly equivalent to the nonthermal systems but higher than the average thermal system O&M costs. Unit costs without disposal for the enhanced systems averaged about a dollar per pound more than the nonthermal systems (roughly \$13 per pound vis-a-vis \$12 per pound) and \$3 to \$4 more than the average thermal system. Disposal costs (\$243 per cubic foot) raised the TLCC for the enhanced systems to between \$3.4 billion and \$3.9 billion over a 20-year period.

A relative health risk study was also conducted (Reference 12) to compare system risks for the worker and the public from application of selected ITTS and INTS technologies. Based on preliminary results, the study did not find major risk differences among the seven thermal and three nonthermal technologies examined.

A time and motion study (Reference 4) was also conducted by INEEL to explore the time-related aspects of the ITTS and INTS systems. The study examined the treatment time for a unit of waste, from receipt to certification for shipping. The purpose of the study was to provide data for research prioritization and allocation of research resources.

A cost impact study (Reference 8) was conducted to identify areas where technology development could have the greatest impact on total life cycle system costs. These were determined by evaluating the sensitivity of system life cycle costs relative to changes in life cycle component or phase costs, subsystem costs, contingency allowance, facility capacity, operating life, and disposal costs. It was found that for all treatment systems (thermal and nonthermal), the most cost sensitive life cycle phase is the operations and maintenance phase, and the most cost sensitive subsystem is the receiving and inspection/preparation subsystem. This is true even on a present value basis.

A preliminary study (Reference 11) of toxic metals and radionuclide partitioning during high-temperature processing of mixed waste was done to identify the need for and the viability of developing the tools capable of describing and predicting toxic metals and radionuclide partitioning in the most applicable mixed waste thermal treatment processes. To date there has been no significant evaluation of relationships between process conditions and partitioning data from past demonstration tests. This lack of evaluation has been due largely to sporadic process data obtained from most tests, a focus of prior tests on demonstrating simple operation of technologies at the expense of understanding the technologies with detailed process measurements, and inadequate diagnostic and measurement technologies.

In the partitioning study a survey of twenty thermal treatment demonstrations was conducted, the data were analyzed, conclusions were made, and recommendations were produced on methods to improve collection of such data and the integrated, predictive models that need to be developed for plasma arc melters. Also, a major recommendation was that further published and raw experimental data from selected existing thermal treatment systems should be evaluated in order to better relate partitioning results to available process data as well as to compare partitioning results from different test systems and treatment technologies.

A study (Reference 3) was performed to analyze the cost and efficacy of constructing a combined waste management/environmental restoration (ER) incineration system. It was assumed that ER waste would be treated by an incineration facility similar to those defined in the ITTS. Two configurations were evaluated: 1) a system (called system ERA-1) similar to ITTS baseline system A-1, consisting of a rotary kiln incinerator and a vitrifier, and 2) a system (called system ERA-7) similar to ITTS system A-7 (Reference 6), utilizing a rotary kiln incinerator operating in a slagging mode, thereby eliminating the need for a primary stabilization unit, and metal melting of the internally-contaminated metal.

The study found that since ER waste was assumed not to be contaminated with alpha material, treating non-alpha waste as alpha waste would require expenditure of funds that could not be justified. Therefore, it appears that the best method of treatment is to keep the two types of waste separated. Combining the alpha and non-alpha systems into a single integrated facility would provide some cost savings by both systems sharing common subsystems. ERA-1 is estimated to save about \$650 million (less than 5% of TLCC) and ERA-7 would save some \$310 million (less than 3% of TLCC).

INEEL conducted another study (Reference 13) to examine issues relating to MLLW waste forms and proposed an R&D plan to undertake an examination of those issues.

OST published a "Summary of Comparative Results" (Reference 20) of the INTS and ITTS studies to describe in more layman's terms the findings of these two major systems studies and detailing the process in which each was conducted.

Finally, a waste storage cost impact analysis was conducted to learn whether it was economically disadvantageous to store, rather than treat and dispose of, DOE's MLLW in anticipation of newer (presumably better) technologies being developed in the future. Using the DOE-MWIR '95 waste inventory (Reference 22), it was found that by treating the waste inventory with *existing* technologies and disposing of it, TLCC are \$4.6 billion. If treatment is delayed to develop new technologies, the costs are \$5.8 billion primarily because an additional 40 years of storage would be required. The study also found that the volume of waste to be stored is reduced by 56% and the cost by 55% if the primary treatment residues are vitrified rather than grouted.

SECTION 2.0

BASES OF STUDIES

Technologies selected for the ITTS Phase 1 study were limited to those believed to be ready for pilot-scale demonstration in 2 years, incorporation into a final design in 3 years, and construction in 5 years.

The study waste stream was based on the 1993 Mixed Waste Inventory Report (MWIR) (Reference 21), subsequently updated in 1995 (Reference 22). This report compiled a breakdown of DOE's MLLW into numerical categories. Further conversations with the specific site data generators were required to develop a more thorough chemical make up of the individual waste streams (Reference 9). The same waste data base was also used in the nonthermal study.

All organics were oxidized to achieve destruction. The ITTS air pollution control (APC) system was designed by a special team of offgas emission experts to ensure that the offgas from the primary treatment system would meet or exceed the emission requirements set forth in RCRA and the Toxic Substances Control Act of 1976 (TSCA) by at least an order of magnitude. Areas of the system designed to treat alpha-contaminated waste were operated at negative pressure to avoid releasing contamination. Bulk metals were decontaminated and recycled. Metals other than bulk lead were melted to remove combustible non-lead products and cast into blocks for reuse by DOE. Elemental mercury was treated by amalgamation. The final waste form was placed in delistable form to reduce the cost of disposal under the RCRA requirements.

The preconceptual designs are based on the assumption that existing (legacy) MLLW and five years of projected generated wastes, will be treated during a 20-year operating period. During such time, the facility was assumed to treat 2,927 pounds per hour operating 24 hours per day, 5 days per week, 240 days per year, at 70% availability (60% for nonthermal) during operation. This is the equivalent of operating 168 days, or 4,032 hours, per year of operation (overall 46% availability). Two central treatment facilities were assumed to work off the existing MLLW inventory from throughout the DOE complex, and transportation costs have been included.

DOE's recognition of the growing importance of stakeholder views in the assessment of technical treatment options resulted in a change being made in the conduct of the INTS. Two technically-trained Tribal and Stakeholder Working Group (TSWG) representatives were added to the technical team; the stakeholder-liaison consultant used in the ITTS was also on the technical team. The TSWG advised both the INTS technical staff (which had produced a compendium of some 250 nonthermal technologies, Reference 23) and a formalized technical support group (TSG) consisting of engineers and scientists from around the DOE complex, EPA, and support contractors. In the last stages of the TSWG's work, a technically-trained Native American consultant was also added to provide relevant input.

The TSWG adopted a set of public-oriented "principles" to guide the evaluation of nonthermal treatment systems R&D needs. These principles generally reflected their concerns, which were

to minimize effluents; minimize effects on human health and the environment; minimize waste generation; address social concerns; provide adequate information to the public; and involve the public in procurements of treatment facilities. These principles complemented the technical criteria developed by technical support contractors: process performance, environmental impact, worker health and safety, costs, and acceptability.

To summarize the studies' bases, they were conducted to compare technologies assembled as complete systems. A comparable basis among the various systems (and among the different studies) was made possible by maintaining the following assumptions throughout all the studies:

- The same waste characteristics and distribution of constituents were used for all analyses.
- All waste coming to the facility was treated by the mainline technology, if possible; otherwise auxiliary processes were used to treat portions of the waste to ensure complete treatment and disposition.
- A single, centralized government-owned and contractor-operated (GOCO) facility capable of treating all DOE MLLW was assumed.
- About 70% of the current DOE MLLW inventory or 236 million pounds of waste was treated over the system lifetime of 20 years.
- Waste was treated at a rate of 3,000 pounds per hour with 45% on-line availability (4032 hours/year of operation out of 8760 hours) due to uncertain equipment life and maintenance requirements with radioactive operations.
- A "best" and redundant air pollution control system was used with backup filtration.
- Except where a Joule-heated melter is explicitly identified, all vitrification is performed in a high temperature plasma furnace that produces a slag.
- Waste loadings (i.e., mass of waste divided by the mass of the final waste form) of 67 wt% in high temperature slag, 50 wt% in polyethylene, and 33 wt% in grout, were assumed.
- Disposal was in a RCRA-engineered on-site disposal facility meeting EPA land disposal restrictions.
- Disposal costs were \$240/ft³ (\$8480/m³).

The actual composition of MLLW stored in drums and boxes is not well known and will not be known until further characterization and operating experience has been acquired. How well the characteristics need to be known in order to treat the waste by various methods is also not

known. To establish a consistent and comparable basis, a waste composition was derived based on the best information available at the start of the study. The reference composition is shown in Table 1. The conceptual facility used for each system was required to process all waste coming into the facility. For example, the mainline thermal process accepted 70% of the waste; whereas, the mainline nonthermal process was able to treat only 20% of the incoming waste directly with the remainder of the waste treated in auxiliary processes.

Table 1. Input Waste Composition

WASTE TYPE	PERCENTAGE OF WASTE INPUT
Inorganic Sludge	35%
Metals	22%
Combustible Debris	14%
Soil	11%
Organic Liquids and Sludges	6%
Special Waste	5%
Non-Combustible Debris	3%
Aqueous Waste	2%
Mercury Contaminated Waste	2%

To ensure all incoming waste is processed, all systems required the same set of subsystems. The following is a summary description of these subsystems:

- Receiving and preparation (or "front-end handling") in which the waste is received and characterized using real time radiography (RTR), gamma spectroscopy, and passive/active neutron (PAN) assay. The waste is removed from the incoming drums, sorted, separated, size reduced, and transferred to the next process.
- Aqueous waste treatment in which all aqueous waste, including secondary waste generated internally, is treated.
- Primary treatment which is the main variable in these system analyses. For thermal systems, primary treatment generally consists of a single process (rotary kiln, plasma furnace, metal melter, etc.) although some variations exist with air pollution system designs and combustion gas. For nonthermal systems, the primary treatment consists of a chemical oxidation process to destroy organic waste plus a separation process (thermal desorption or washing) to remove organics from inorganics waste matrices.

- Melters are generally used for ferrous metal wastes that cannot be decontaminated to produce ingots for subsequent recycle within the DOE system. However, one system (G-1) also uses a metal melter for primary treatment.
- Metal and lead decontamination uses an abrasive water jet to decontaminate metals for recycle and to decontaminate drums for reuse.
- In thermal systems, mercury is removed from inorganic wastes with a retort and in nonthermal systems it is removed by a leaching process. The mercury metal is then amalgamated for disposal.
- Special wastes are highly variable, and treatment processes in large part are undefined. Thus, funds were identified for treatment, but no treatment process was identified.
- Primary stabilization is accomplished by a high temperature vitrifier (or slag former) for most thermal systems. Grout is used for one thermal system and for most nonthermal systems. One nonthermal system uses phosphate bonded ceramic (cement) (PBC) for primary stabilization. All systems require polyethylene for secondary stabilization of soluble or volatile salts.
- The secondary waste (new generation) from the APC subsystem of thermal treatment units will likely result from capture and immobilization of volatile materials. Low temperature immobilization (e.g., polyethylene) was assumed in all studies to contain the materials volatilized from the thermal treatments.

SECTION 3.0

THERMAL SYSTEMS

3.1 System Descriptions

Two thermal system study planning meetings were held in mid-1993, involving scientists, engineers, and program managers from throughout the DOE complex; EPA representatives; and private engineering and pollution control contractors, to determine which thermal technologies should be fashioned into complete systems to undergo analyses under ITTS Phase 1. In early 1994, a meeting at DOE headquarters, primarily involving EM users, resulted in the selection of the systems and subsystems listed in Table 2 for evaluation. A more detailed description of these systems is contained in References 6 and 7. All the systems (both thermal and nonthermal) contain all the subsystems required to treat the incoming waste streams shown on Table 3, as well as internally-generated waste.

System A-1 A rotary kiln system that represents the typical incinerator using air for the combustion gas and vitrification for waste stabilization.

The technical experts gathered to select the systems for study were adamant that DOE could build publicly-acceptable thermal treatment units if a first-class APC system were included in the offgas subsystem. Accordingly, a "Cadillac" APC system serves as the standard for each system unless otherwise noted. The baseline APC system consists of a dry gas filtration unit (baghouse or ceramic filters followed by HEPA filters), a wet gas scrubbing unit (water quench, hydrosonic and packed-bed scrubbers, nitrogen, and dioxin removal subsystems), a system for continuous emissions monitoring (CEM), activated carbon filters for mercury removal, continuous radiation samplers, and dual HEPA filter banks.

System A-2 The same as A-1, but with oxygen for combustion gas. This allows comparison of the offgas from a minimum offgas thermal system with the gaseous effluent from nonthermal systems.

System A-3 The same as A-1, except the APC system uses all wet filtration and cleaning techniques and the baghouse is eliminated.

System A-4 The same as A-1, except the incinerator uses oxygen as the combustion gas and a different APC configuration is used. This APC system treats offgas by the conventional dry filtration method and then removes carbon dioxide by absorption into lime in a fluidized bed for delayed release.

Table 2. Thermal Systems and Subsystems Evaluated in the ITTS Studies SYSTEM	DESIGNATION	TREATMENT		STABILIZATION	METALS
		INORGANICS	ORGANICS		
Rotary Kiln (RK) w/ air for combustion and Dry/Wet APC	A-1	RK	RK	Vit. & Polymer	Decon/Melter
RK w/ oxygen for combustion and Dry/Wet APC	A-2	RK	RK	Vit. & Polymer	Decon/Melter
RK w/ air for combustion and Wet APC	A-3	RK	RK	Vit. & Polymer	Decon/Melter
RK w/ oxygen for combustion and CO ₂ retention	A-4	RK	RK	Vit. & Polymer	Decon/Melter
RK w/ air for combustion and polymer stabilization	A-5	RK	RK	Polymer	Decon/Melter
RK w/ air for combustion and salt recycle	A-6	RK	RK	Vit. & Polymer	Decon/Melter
Slagging Rotary Kiln	A-7	RK	RK	Slag & Polymer	Decon
RK w/ air for combustion and grout stabilization	A-8	RK	RK	Grout & Polymer	Decon/Melter
Indirectly Heated Pyrolyzer and Dry/Wet APC	B-1	Pyrolyzer	Pyrolyzer	Slag & Polymer	Decon/Melter
Plasma Furnace w/ air and Dry/Wet APC	C-1	Plasma	Plasma	Slag & Polymer	Decon
Plasma Furnace w/ CO ₂ retention	C-2	Plasma	Plasma	Slag & Polymer	Decon
Plasma Gasification	C-3	Plasma	Plasma	Slag & Polymer	Decon
Fixed Hearth (FH) w/ oxygen and CO ₂ retention	D-1	Vitrifier	FH	Polymer	Decon/Melter
Debris Desorption w/ RK for combustibles	E-1	Desorber	RK	Grout/Vit./Poly.	Decon/Melter
Molten Salt Oxidation (MSO)	F-1	Vitrifier	MSO	Polymer	Decon/Melter
Molten Metal (MM) Waste Destruction	G-1	MM	MM	Slag & Polymer	Melter
Steam Gasification	H-1	Vitrifier	Gasifier	Polymer	Decon/Melter
Joule Heated Vitrification	J-1	Vitrifier	Vitrifier	Polymer	Decon/Melter
Thermal Desorption & Mediated Electrochemical Oxidation	K-1	Desorber	MEO	Grout & Polymer	Decon/Melter
Thermal Desorption & Supercritical Water Oxidation	L-1	Desorber	SCWO	Grout & Polymer	Decon/Melter

Notes: In all systems, contaminated metallic or elemental mercury is amalgamated for stabilization and disposal. Uncontaminated mercury is recycled. Stabilization of secondary wastes and slats is in polymer. Surface contaminated metals are decontaminated and metals with entrained contamination are treated in a metal melter.

Ash is stabilized in the slag from the thermal treatment unit, polymer is used for secondary stabilization of salts.

Metal is treated in the thermal treatment unit, polymer is used for secondary stabilization of salts.

MEO and SCWO treat only organic wastes.

Grout for desorbed noncombustibles, vitrification for bottom ash, and polymer for secondary wastes and salts.

System A-5 The same as A-1, except that primary stabilization is polymer, rather than vitrification. All solid residues are stabilized by polymers; however, bottom ash and fly ash stabilized residues are kept separate for purposes of tracking transuranic activity.

System A-6 This system is designed for maximum recycling and minimum volumes of disposed waste. An air-fired rotary kiln is preceded by a feed preparation subsystem that maximizes decontamination to permit recycling of waste materials, containers, bulk metals, and process chemicals. Aqueous secondary waste streams, except acid gas scrubber blowdown, are treated in an aqueous waste treatment subsystem. The blowdown is processed through a salt splitting system to produce a caustic and hydrochloric acid. The caustic can be recycled to the beginning of the wet section of the APC subsystem. Salt splitting is a specially designed electrodialysis process resulting in caustic being regenerated for reuse. Activated carbon filters in the offgas line are recycled using a retorting process, which removes mercury. HEPA filters in the APC system use stainless steel cloth (rather than cloth or manufactured fibers) that is reusable.

System A-7 Slagging rotary kiln, which stabilizes waste directly in a slag, thereby eliminating the vitrifier. Internally-contaminated metal is also treated in the kiln, eliminating the metal melter, as well as the possibility of recovering and recycling internally contaminated metals.

System A-8 The same as A-1, except grout is used to stabilize the ash from the primary treatment system rather than the vitrifier. This allows comparison of a thermal system with nonthermal stabilization to the nonthermal systems studied in the subsequent INTS study that are precluded from using thermal stabilization technologies. System A-8 was added after Phase 2 was concluded to provide a new baseline (off-the-shelf technology for both primary treatment and waste stabilization) to the ITTS and INTS study comparisons.

System B-1 A pyrolysis system that is indirect, electrically fired using a rotary kiln pyrolyzer and a secondary combustion chamber (SCC) using oxygen combustion gas with the vitrification unit. The oxygen starved atmosphere in the kiln produced the least amount of offgas, but the pyrolysis gas is oxidized with pure oxygen in the SCC, which is followed by a standard wet-dry APC subsystem. The APC system

is smaller due to the smaller offgas volume. The presorting requirements are much greater since most noncombustible bulk material must be separated before entering the pyrolyzer.

- System C-1   Similar to A-7, except that a plasma furnace is used in place of the rotary kiln. Thus, the vitrifier and metal melter are eliminated, but an innovative thermal technology is used.
- System C-2   A plasma furnace using oxygen as the combustion gas. The APC subsystem uses a delayed release system to retain the carbon dioxide and recycle the oxygen (the same as A-7).
- System C-3   Using a different plasma concept (a fixed hearth melting pot instead of a rotary pot), this melter requires a freeze valve or similar mechanism for discharging the vitrified solids from the reactor since there is no centrifugal force as in C-1 and C-2. Air is the torch gas and steam the oxidant. The waste form is a vitrified slag, the packaging of which is required for primary stabilization. Generated offgas can be sent to a steam boiler for energy recovery.
- System D-1   This system retains the carbon dioxide. It combines a substoichiometric, fixed-hearth primary combustor (i.e., a controlled air incinerator) with an SCC, both using oxygen as combustion gas. A fluidized bed absorber is used to absorb the carbon dioxide in lime after going through the APC. The carbon dioxide is monitored for RCRA compliance, radioactive compounds, and delayed released.
- System E-1   This thermal desorption system takes advantage of RCRA land disposal regulations that permit treatment of waste classified as debris by grouting only. A standard air-fired kiln is used. The incineration is standard except for a thermal desorption step parallel to the thermal treatment unit. The desorber separates volatile organic compounds (VOCs) from debris as defined by RCRA. Waste components vaporized in the desorber and organics recovered from aqueous waste treatment are recycled to the rotary kiln. All solid residues other than ash go into grout for stabilization. Ash goes to a vitrification unit.
- System F-1   Molten salt oxidation in which combustible waste is oxidized in a molten salt bed; the molten sodium carbonate acts as a catalyst. The bed also neutralizes halogenate acids and forms halogenated salts. Noncombustibles, such as metal and salt, collect in the bed and are removed by continuously transferring some salt from the 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 is recovered and recycled back to the molten bed.

- System G-1 A new molten metal technology that eliminates the need for a vitrifier and metal decontamination. All combustible and noncombustible waste and all metals (except lead and mercury) are reported to be treatable in a single metal melter, thereby eliminating several ancillary operations. The metal melter is operated in a reducing environment to produce a syngas combusted in a catalytic oxidizer so the APC system is small.
- System H-1 In this new technology, combustible and noncombustible waste must be separated as in nonthermal systems. Combustible material is treated in a steam gasifier in a reducing mode to produce a combustible syngas that is burned in a secondary combustion chamber. Noncombustible wastes are treated directly in a vitrifier capable of treating organically-contaminated solids.
- System J-1 This system is designed around a conventional glass-making joule-heated melter in a one-step oxidation/vitrification process for treating both combustible and noncombustible waste.
- System K-1 In a flameless, low temperature (600° F) manner, system K-1 uses thermal desorption and mediated electrochemical oxidation (MEO) to heat combustible and noncombustible solids to vaporize low-boiling-point VOCs. MEO is used to destroy the organic liquids, in which a liquid electrolyte converts the organics into gaseous effluents.
- System L-1 In a flameless, low temperature (800° F) manner, system L-1 uses thermal desorption and supercritical water oxidation (SWO) to heat combustible and noncombustible solids to vaporize low-boiling-point VOCs. In the SWO reactor, supercritical water above 705° F and 220 atmospheres oxidizes organic wastes to gaseous effluents. In supercritical water, organic compounds that are normally immiscible in water, are miscible. Inorganic compounds, such as salts, are almost completely insoluble in supercritical water. In SWO, quick and complete oxidation of organic waste is obtained using pure oxygen or hydrogen peroxide as the oxidant.

Table 3. Total System Input for Thermal and Nonthermal Systems

THERMAL SYSTEM INPUT		NONTHERMAL SYSTEM INPUT	
TYPE OF WASTE	MASS FEED RATE(lb/hr)	TYPE OF WASTE	MASS FEED RATE(lb/hr)
Combustible Organic Liquids, Sludge, and Soft Debris	660	Organic Liquid and Sludge Waste	185
		Soft (Combustible) Debris	435
Noncombustible Solids (Process Residue, Soil, and Open Debris)	340	Process Residue & Inorganic Sludge	1007
		Bulk Soil	329
		Open Nonmetal Debris	80
Metal with Fixed or Internal Contamination	149	Complex Debris (Internally Contaminated Metal, Firebrick, etc.)	177
Open Metal Debris with Surface Contamination	468	Open Metal Debris with Surface Contamination	462
Lead	26	Lead	26
Aqueous Waste	80	Aqueous Waste	61
Mercury Contaminated Waste	50	Mercury Contaminate Waste	50
Special Waste	153	Special Waste	155
Sulfide and Halide	1	Sulfide and Halide	7
TOTAL	2927	TOTAL	2927

NOTES: Includes 3 lbs/hr of metallic mercury, 22 lbs/hr of soft debris, and 25 lbs/hr of complex debris. It is assumed that 50% of the drums are surface contaminated and can be decontaminated and recycled. The other 50% are internally contaminated and are treated as complex debris in nonthermal systems and sent to a metal melter in thermal systems. It is also assumed that all bins are fiber-reinforced plastic and are classified as soft debris in nonthermal systems or combustible solids in thermal systems.

3.2 System Performance

System performance was essentially measured by the amount of offgas, waste water, and solids the systems "threw off". Generally, the lower those amounts were, the better. Another measure was the amount of metals that were available for recycle, in which case the higher amount, the better. The following table compares the performance of seven different systems evaluated in the study.

Table 4. Comparison of Effluents of Some Selected Thermal Systems (in lbs/hr)

System	Offgas	Waste Water	Metal to Recycle	Solids to Disposal
Rotary Kiln(RK) w/melter, A-1	20,700	400	620	1930
RK w/melter, oxygen comb.A-2	5,870	890	620	1930
Slagging RK, Air comb., A-7	26,400	780	490	2100
Rotary Kiln w/ grout, A-8	20,900	-36	620	3670
Plasma, Air combustion, C-1	6,900	460	660	1860
Metal Melter, Reducing, G-1	11,590	87	640	1790
Steam Reforming, Reducing H-1	11,650	-490	620	1930

Note: Energy costs are a much lower portion of TLCC than previously assumed. High energy use is usually associated with vitrification systems for stabilization of the inorganic residues. The ITTS studies showed that, when viewed as a percentage of TLCC, the energy costs are only about 1%. Table 4 presents comparative data on selected thermal energy costs, chemical reagents, and transportation.

Table 5. Comparison of Energy, Reagent Usage (excluding waste stabilization reagents), Total Incoming Transportation Requirements (including waste, reagents, stabilization materials), and Total Outgoing Loaded Transportation Requirements (including waste to disposal and recycled metals to storage)

SYSTEM	ENERGY COST (\$/h)	CHEMICAL REAGENT USAGE (lb/h)	TRANS. REQUIREMENT	
			INCOMING (trucks/yr)	OUTGOING (trucks/yr)
Rotary Kiln (RK) w/melter, System A-1	47.33	83	341	234
RK w/melter, oxygen comb., A-2	35.25	83	341	234
Slagging RK, Air comb., A-7	33.36	83	346	237
RK w/ grout, A-8	20.03	83	493	393
Plasma, Air combustion, C-1	163.54	83	339	231
Metal Melter, Reducing, G-1	215.08	83	327	223
Steam Reforming, Reducing, H-1	50.42	83	341	234

3.3 System Costs

The following table indicates total life cycle costs (TLCCs) of the thermal systems:

Table 6. Total system life-cycle cost estimates (not including transportation) (in thousands of dollars).

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	1,093,648	266.24	2,472.85
A-2 Rotary kiln, oxygen	9.34	0.999	7.98	0.999	13.6	2,204.99	1,093,648	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, CO ₂ retention	9.90	1.059	8.46	1.059	19.7	2,336.83	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	1,093,648	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, CO ₂ 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, CO ₂ retention	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
I-1 Joule-heated vitrification	8.14	0.871	6.96	0.871	13.6	1,921.59	1,093,217	266.14	2,187.73
K-1 Thermal desorption and MBO	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 584 lb/hr.

3.4 System Evaluation

Systems were evaluated for regulatory compliance; environment, health, and safety (ES&H); treatment effectiveness; implementability; stakeholder concerns; life-cycle costs; and technology development required.

System A-1 The baseline system for the entire study, System A-1, uses proven commercial technologies with a majority of its components having previously been used in widely available hazardous waste applications. Key technologies in the system are a rotary kiln, a dry offgas unit equipped with a quench, a baghouse, activated carbon absorbers for mercury removal, a bank of HEPA filters, and a wet offgas unit with a hydrosonic scrubber and packed tower acid-gas scrubbers.

Similar systems have been widely permitted, and this system is designed to meet the TSCA performance standards for PCBs. The vitrified final waste form is expected to meet land disposal restrictions (LDRs). ES&H requirements are met by design characteristics consistent with safe commercial operation. Exposure of workers to alpha radiation is met by triple containment of those portions of the system where exposures might occur.

With respect to implementability, the rotary kiln incinerator is a commercial technology for hazardous waste and is currently employed at Oak Ridge National Laboratory (ORNL) for mixed waste organic liquids. The newly-operational Consolidated Incineration Facility at the Savannah River Site (SRS) is also based on a rotary kiln concept. Key areas that had to be evaluated for improvement were rotary seals and refractory life.

It is recognized that incinerators instill distrust among many in the public. To ensure a more favorable perspective, the ITTS APC concepts were "over-designed" for all thermal and nonthermal systems, with particular emphasis on System A-1's basic APC system. With redundancies, inclusion of a myriad of units and subsystems, and a design that keeps the offgas temperature clearly out of the dioxin reformation envelope, the study designers were sensitive to stakeholders' concerns. Another added-in factor was the leach-resistant, high-integrity waste form produced by this system. This waste form will minimize the release of hazardous material to groundwater over the long term.

Cost risk is low on non-alpha MLLW because this system has previously been used on this type waste. If the system were applied to alpha wastes; however, the risk of cost overruns would be high as further development on the ease of decontamination and maintenance is required.

The baseline technology is conventional and is ready for application on schedule. Significant delays are not expected.

- System A-2 This system is the same as A-1 exception that oxygen is the combustion gas to minimize offgas volume. The substitution of oxygen raises the concern that system compliance with air pollution limits might be jeopardized as the same quantity of contaminants will now be entrained in a smaller volume of offgas. However, further examination found this not to be the case except for NO_x. If the flow of dilution air alone is reduced, but not the mass of pollutants, then the use of oxygen is not justified. Technology risks are potentially greater because maintaining precise oxygen control in the kiln is more difficult. Dynamic seals are also required at each end of the kiln. While oxygen-fired furnaces have been widely used in industrial applications, there has been very limited application to treating hazardous wastes with oxygen flames.

Key areas requiring system integration or development are the oxygen burner design, flame propagation and control, prevention of ash slagging, and NO_x control.

- System A-3 The wet APC system is a minor variation of A-1. The APC system does not have a dry filtration step. The change was made to study the effects of using a totally wet APC subsystem. Only minor differences occur in technology risk, primarily with respect to mercury management which will not be captured by the wet scrubber causing the addition of a mercury removal step before polymer stabilization. The system also may be less desirable from an ES&H point of view due to the larger final waste volume caused by the capture of fly ash in the scrubber liquor.

- System A-4 A CO₂ retention unit was added to the end of the APC system providing the capability to delay the discharge of the offgas and eliminate the stack. The delay is accomplished by absorbing the carbon dioxide in lime and desorbing it later in a calciner. This retention acts as a check point for the offgas discharge and helps prevent inadvertent discharge of pollutants to the atmosphere. To accomplish this, the system has three main differences from A-1: an oxygen burner in the kiln, the APC subsystem has only a dry filtration unit, and the addition of a CO₂ unit. The technology and regulatory compliance risks are higher, especially with respect to the metals-removal aspect of the system. Development of a zero air in-linkage system, better sampling methods for detecting contaminants in spent lime, methods for separating and releasing accumulated inert gaseous and solid compounds, and the development and integration of process controls is required.

Due to the extreme immaturity of delay and release technologies, developing costs on this system was problematic and uncertain. The major technical concern is

probability of air in-leakage to the kiln. Due to oxygen and nitrogen build up in the kiln, and without the option of blowdown, the volume of the offgas will be increased by an estimated 25% in the first hour of operation. High air in-leakage renders the benefit of the oxygen recycling feature of this system questionable. Additionally, ash slagging could occur frequently due to the high temperature of the oxygen flame. The fate of the radionuclides must also be determined.

Stakeholder groups advising DOE have expressed their support for a delayed release concept, since the possibility of unmonitored or uncontrolled release of pollutants is greatly reduced. However, the extreme technical complexities added by this system pose serious questions (see also System D-1).

- System A-5 The same as A-1, except the vitrification unit has been eliminated and all solid residues are stabilized using polymer. Eliminating the vitrifier reduces technical uncertainty with the only concern being the acceptability of a polymerized waste form for long-term isolation of alpha MLLW. Additionally, a greater ES&H risk results from higher volumes of final waste which might be viewed less favorably by permittees and local stakeholders.
- System A-6 The maximum recycling system is the same as A-1, except the features added to achieve minimization of waste requiring disposal. Three differences are made from baseline: spent activated charcoal saturated with mercury is recycled, a metal solids separation unit is added to the incineration feed prep unit to capture metals to be recycled, and a salt recovery subsystem is added to crack and recycle the scrubber salts. Only the salt recovery subsystem poses a technical risk, as a salt cracker must be developed. The front-end handling system must also be redesigned for efficient metals recovery. Maximum recycling/waste minimization would likely be looked on with favor by regulators and the public.
- System A-7 The slagging rotary kiln is a proven commercial technology permitted around the United States and in Europe. Process-related regulations can be met through standard permitting processes, and the final waste form is expected to meet or exceed LDR standards. The slag produced by the slagging kiln in hazardous waste applications has not, in practice, always been a consistent, leach-resistant product. However, optimizing slag characteristics through minor changes in operations is not difficult. It is recommended that when treating DOE MLLW, a constant feed of glass-forming solids be maintained to ensure a high quality leach-resistant product. In this study a contaminated soil addition of 50% (by weight) is assumed. Fewer contaminants are found in the offgas of the slagging kiln than in conventional kilns, as residence time in the kiln is greater to permit slag formation. This permits effective destruction of PCBs, lower particulate loadings (reducing precursors for dioxin formation), and more efficient exothermic reactions of the waste.

Technology risk is substantially the same as the baseline system. The refractory life might be a bit shorter due to higher operating temperatures, and the APC system is slightly larger to accommodate higher offgas volumes.

System B-1 The major purpose of the pyrolysis primary destruction unit (with vitrification and incineration gas APC combined) in this system is to limit the use of oxygen for combustion to provide the lowest possible offgas volume. Another advantage of the pyrolyzer is that a refractory liner normally found in an incinerator is not required as this unit operates at lower temperatures. Components are all commercially available but require engineering development and demonstration.

Operational differences from the baseline are: a more extensive waste receiving and preparation unit is required as noncombustible material must be separated out; the indirect-fired pyrolyzer operates at 900° F and an SCC operates at 2,200° F, both using oxygen for combustion; a single APC unit is used for both the incinerator/furnace and the vitrifier; only combustible waste is fed to the incinerator; and noncombustible debris and other solids are pretreated and fed directly to the vitrifier after being shredded and dried to remove water vapor.

Trace organics in the noncombustible material could further complicate the dryer operations, and the vitrifier operation could be complicated by organics as well. Incomplete combustion in the pyrolyzer could result in a high-carbon ash, which might affect the quality of the glass waste form.

On the positive side, the volume of discharged offgas is one-sixth that of the baseline, possibly gaining more acceptance from the public and permitting authorities.

System C-1 The plasma arc furnace technology utilized for the metallurgical industry is applied because of its versatility with high control of intake air flow rates. Differences from the baseline are the arc furnace for the kiln and the addition of an electrically-fired SCC using combustion air. There is no vitrifier as the plasma furnace operates as a slagger. There is no metal melting subsystem as the furnace is also used for that purpose.

The technology risks are considered higher than baseline based on the lack of commercial experience. While the plasma furnace is in a very advanced development stage, it cannot be considered commercial, especially for MLLW. Components are all commercially available but require engineering development and demonstration.

While the plasma arc furnace will have a higher DRE for organics, it complicates the management of volatilized metals due to the high temperature of the arc.

Development efforts will be needed to determine the fate of vaporized metals and volatilized actinides in the offgas. A sand filter could be added to serve as a cold trap. Electrode life is an area in which great development strides have been made, but where more work is needed. The type of refractory lining in the furnace must also be explored more fully.

System C-2 The use of the rotating plasma arc furnace eliminates the need for a separate vitrification furnace as the operating temperature is sufficiently high to produce a vitrified slag. Similarly, the metal melting subsystem is eliminated as metals are melted in the furnace. The system uses oxygen as the torch gas. Offgases go to an SCC and into the APC and then pass several separation steps where specific products or contaminants such as water, carbon dioxide, acids, particulates, and mercury are removed. The remaining offgas stream, mostly oxygen, is then recycled to the furnace. Carbon dioxide removed in the APC is stored in delay tanks. The technology risk is higher than baseline due to lack of commercial operation, higher corrosion rates of components, and the likely shorter lifespan of refractory due to the higher operating temperatures.

Plasma furnaces are regulated as incinerators, and this system should not have permitting problems. The vitrified final waste form should exceed LDR requirements. The expected environmental advantages described in A-4 for delayed carbon dioxide apply to C-2. However, this feature also entails increased complexity and size of the APC system, which in turn increases risk to the workers.

Implementability concerns involve the limited plasma torch electrode life in which DOE has devoted considerable development, although performance is only about 100 hours. While not jeopardizing destruction efficiency, shorter torch life reduces system availability and increases costs. It also entails ES&H problems due to worker exposure from constant changeouts when operating on DOE MLLW. Limited refractory lifetime and ease of refractory replacement raise the same issues.

System C-3 This is a different plasma concept using a nontransferable direct current arc electrode containing both the anode and the cathode in a fixed (rather than a rotating) pot or melter. It is being developed in this country with a focus on the destruction of medical wastes or other waste streams with high (90%) organic content. Since there are no centrifugal forces in the hearth, a release valve is required for discharging the vitrified solids; however, costs and mass balances between C-2 and C-3 are similar.

Technology risks are higher than the baseline system because of the relative lack of commercial experience; C-3 shares this and the other C-1 and C-2 technology

risks. As a steam reforming process that does not use a flame or an SCC, this system could be classified as an industrial furnace and permitted under the regulations for boilers and industrial furnaces or as a RCRA "miscellaneous" facility. Its slagged final waste form should meet LDR requirements. Another technology risk is the feeding system which requires careful feeding of organics with the appropriate volume of inorganics to maintain the reducing nature of the system.

While being equal to or better than the baseline system in destroying organic contaminants, the management of volatilized metals is complicated due to the high temperature created by the plasma arc. This is further complicated by its operating in the 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. Emissions of nitrogen oxides and dioxins in the system should be less than baseline, as the reduced atmosphere discourages their formation, and emissions volumes are halved.

Besides the worker exposure problems cited in C-2, other problems may be present due to the possible pyrophoric nature of the suspended metals in metallic form and the need to manage hydrogen and carbon monoxide carefully (syngas, created at the rate of more than 1000 pounds per hour) to avoid explosions and other safety risks.

System D-1 This system is designed to discharge the least amount of waste gases into the atmosphere using a fixed hearth, controlled air incinerator fired by oxygen. Only combustible waste will be fed to the furnace with the remainder sorted and fed directly to the vitrifier. A CO₂ retention unit has been added to delay the discharge of offgas from the incineration APC (see System A-4). This system is considered to have a higher technology risk than baseline.

Emission concerns are the same as those described for A-4. While it is generally believed that the system may reduce emissions, some areas of uncertainty must be studied further. Key concerns are the low level of process maturity and the lack of adequate operating data and knowledge to assess the feasibility and efficiency of the carbon dioxide retention system. However, the delayed release features allow for assurance and measurement that released offgases meet regulatory requirements and inadvertent releases are prevented. These factors might result in better acceptance of a thermal treatment facility by state and local regulatory agencies and the public.

Technology risks are posed by the higher demands placed on the sorting system, as compared with baseline, since the complexity and size of the receiving and

prep subsystems are increased. For successful carbon dioxide retention, a furnace design that minimizes air in-leakage must be chosen and constructed.

The main component of the carbon dioxide retention subsystem is a circulating fluidized bed of lime that absorbs the gas from the offgas stream, permitting delayed release. While this is a well-known process, its application in this manner is new, and a prototype would have to be built and operated. The lime is recycled. A low lime recycling efficiency could greatly affect the final waste volume requiring disposal. Other capture methods might prove more suitable than the lime-based process.

System E-1 The distinguishing aspect of this system is the thermal desorption of debris to take advantage of the recent debris rules published by EPA. These rules permit minimal processing and stabilization of a certain category of MLLW debris (trash-like material), thereby reducing incoming waste processing. In this system, debris goes through the desorber, and offgas is condensed and sent to the incinerator. A grout mixer stabilizes the solids from the desorber.

The system is considered a higher technology risk than baseline primarily due to the extensive sorting requirements of the thermal desorption unit, which will be as large as the incinerator. Final waste volumes will be higher (although offgas volumes will be lower), and the waste form will be less stable. Unless operating temperatures are kept low, plastic material in the debris will melt, stick to the desorber internals, and possibly plug the unit. The unit could also be plugged by large pieces of other agglomerated solids formed in the desorber. This causes a quandary: at low operating temperatures, the benefit of a thermal desorption process to remove organic material is limited.

The addition of a thermal desorber subsystem adds higher technology risks to the baseline system, including extensive storing requirements and the design strategy for the desorption, including, but not limited to, proper operating temperatures and ways to accommodate or eliminate materials melting or agglomerating while obtaining good organic desorption.

System F-1 In the molten salt oxidation (MSO) system, combustible waste (33% of the total DOE inventory) and air are combined in a bed of molten salt (sodium carbonate), which serves to provide a contact surface for oxidants and waste, catalyzes oxidation reactions, and neutralizes acids in the waste. Scrubbing of the acids in the molten bed eliminates the need for acid gas scrubbing in the APC. The noncombustible debris and other solids in the DOE MLLW stream are pretreated and fed directly to the separate vitrifier in the primary stabilization subsystem. Because of the need for separating the combustible from the noncombustible, a more extensive waste receiving and preparation subsystem must be included.

This system has a greater technology risk than baseline. A complete review of the MSO technology was conducted for DOE in December 1993 (Reference 5). MSO has been developed over many years by the DOE Office of Fossil Energy with only limited commercial operation for other purposes (i.e., waste destruction) and is not known to have been previously permitted for waste applications. It is likely to be permitted as either an incinerator or under RCRA's miscellaneous category. The noncombustibles and ash from the main reactor are fed to a separate vitrification system expected to produce a vitrified solid meeting or exceeding LDR requirements. The system should be equal to or more efficient in destroying organic contaminants than the baseline. Emission volumes are halved, as compared with baseline, and NO_x emissions are reduced due to lower operating temperatures. However, worker exposures are increased due to the increased waste separations at the front end and the addition of equipment for salt recycling. Although MSO can process a variety of wastes, it is more efficient when only organics are processed. It requires significant development work to refine waste handling, treatment, and disposal requirements. Corrosion problems with the reactor vessel have been a concern.

MSO waste feed must be one-eighth inch or smaller to facilitate feeding and to improve reactor kinetics, making the baseline system more versatile. MSO also works best with feed containing a low inorganic content. 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 a typical cross-section of DOE MLLW shows that the inorganic percentage could be as high as 16%. This means that the combustible waste input may already have an inorganic concentration near the 20% allowable limit for MSO. This high inorganic component means that a higher volume of spent molten salt must be continuously withdrawn from the bed to keep the inorganic or ash content below 20%. In turn, this increases the size of the salt recycle subsystem, which must be sized to process a sufficient volume of salt/ash to maintain less than 20% inerts in the salt bed.

System G-1   This system employs a molten metal reactor operating at over 3000° F and at various operating pressures ranging from negative to highly positive to destroy a wide range of DOE MLLW stream components. An initial charge of 2000 to 3000 pounds of metal is fed to the reactor and melted to provide the heat source and the molten metal destruction bath. Additives or reagents such as lime and flux are fed to the reactor on demand, using nitrogen gas for delivery.

Aqueous and sludge wastes are injected into the molten bath at the bottom of the reactor; shredded solids are fed by lances below the surface of the molten bath. Through DOE development funds, work has been performed to increase the size of this solid feed and still maintain destruction efficiencies. The high thermal

energy and catalytic effect of the molten metal disassociates the feed into basic constituents, which dissolve into the metal. Once dissolved, elemental reformations and phase separations into gaseous slag (called "ceramic" by the vendor) and metal phases can be obtained by adding reactants. 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 (which may be of industrial quality and can be recycled) is extracted from the process and cast into molds. Slag is tapped off into crucibles, allowed to cool, and then capped and sealed, resulting in a stabilized waste.

Overall, the risks of this system are higher than the baseline, primarily due to the lack of commercial experience. A DOE technical team completed a technical evaluation of this technology for EM in March 1996 (Reference 23).

If successfully demonstrated, this system can pose a number of advantages over the baseline system in treating DOE MLLW. The thermal destruction and primary stabilization are performed in one step, reducing the amount of equipment, space, and handling required. Treated metal can be recycled throughout the DOE complex and used as containers or for shielding in HLW containers. The reactor also produces less offgas than the baseline thermal subsystem.

While the high temperatures would intuitively cause one to believe that this system would be regulated as an incinerator, it has been successfully regulated in several states as a recycler under RCRA. The final waste form is a vitrified solid, which would meet LDR requirements. The DRE's are expected to meet regulatory standards. The vendor has performed successful tests that enabled the contaminants (including surrogates for radionuclides) to remain in the desired end form (either slag or gas). One outcome of this is that radioactively-contaminated metal can be cleaned with a high decontamination factor, rendering it suitable for recycling.

Major development work is required in melter design, removal of slag and molten metal, cooling, and packaging—all at relatively high temperatures. The process is potentially capable of significant volume reduction by providing organic destruction, inorganic material vitrification, and metal separation functions in one step.

System H-1 The steam gasification system differs significantly from A-1. The thermal treatment subsystem is 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 minimize offgas generated. Only combustible waste is fed to the

reactor; noncombustible debris and other solids are pretreated and fed directly to the vitrifier. Because of the need to sort the combustible and noncombustible materials in the feed, the receiving and preparation subsystem is larger than baseline.

This system is in an advanced development stage and has been used commercially for treating biomass waste, but overall it is considered a higher technology risk than the baseline when applied to DOE MLLW as there is no experience on the radioactive component. Also, there is some concern over the destruction effectiveness of a system with no SCC. Steam gasification is a commercial process and is expected to be readily permitted under industrial furnace regulations. The final waste form is a vitrified solid that should meet LDR requirements. However, hydrogen gas, a product of the organic destruction, is produced and must be safely handled. The fate of radionuclides and volatile metals must also be understood; however, nitrogen oxides, dioxin, and furan formation are discouraged in a reducing atmosphere. The offgas volume is somewhat reduced compared with the baseline, although it can only treat combustible waste in particles less than one-quarter inch which have been dried. All of this enhances complexity and raises effectiveness and implementability concerns.

System J-1   The joule-heated vitrification process has been used to treat radioactive waste and MLLW. It vitrifies the noncombustible waste and oxidizes the combustible waste. The thermal treatment subsystem has an electrically heated melter unit, head space for organic oxidation, and operates at 2700° to 3000° F. The need for a primary stabilization subsystem is eliminated, since thermal treatment and vitrification are combined.

J-1 has a higher technology risk than the baseline system. It can treat either combustible or noncombustible waste, although the effectiveness on the former must be assessed. It can operate in either oxidizing or reducing mode, the latter producing a syngas of hydrogen and carbon monoxide. It will probably be permitted as an incinerator, although it could be considered a nonflame thermal treatment process. Volume emissions are one-third that of the baseline, and worker exposures compared with the baseline are reduced due to the elimination of the vitrifier.

Limited feedstock sorting will increase system availability; however, more sorting is required than in other one-step processes evaluated such as the slagging rotary kiln and plasma vitrification. Metals content is limited to 20% of the feed, and metal drums cannot be directly fed into the melter. There has been no experience on actual DOE MLLW.

System K-1 The reason for inclusion of the 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 debris rule for hazardous waste processing, allowing minimal processing and stabilization of "trash-like material" contained in MLLW. This system uses low-temperature processing and is likely to be perceived as a nonincineration technology. The system uses TD as a thermal treatment technology combined with MEO for processing organic liquid wastes. (MEO is inappropriate for treating solid waste streams and was combined with TD to achieve a total treatment approach.) Condensed gas from the TD is also sent to the MEO. Solids leaving the TD are grouted, not vitrified.

Thermal desorption is a commercial and permitted approach for hazardous waste treatment, usually contaminated soils. MEO would probably be permitted as an aqueous treatment method. Grouting produces a less stabilized waste form and a larger volume than the baseline system, and this waste form should be evaluated for regulatory acceptability. Process control will be complicated due to waste variability and more waste characterization may be required. The effectiveness of the TD in volatilizing the combustible waste fraction has not been determined. It must operate in a low oxygen environment. The combustible waste could generate noncondensable combustion products, which must then be sent to thermal oxidation.

Emissions are produced by the TD, APC, and the MEO processes. The MEO process produces a hydrogen stream that could include volatile organics as well as a separate stream containing carbon dioxide and chlorine. A scrubber removes the chlorine; the remaining two streams are directed to a thermal oxidizer, which is a proven and effective treatment system. Recovery of mercury from the TD process is also problematic.

Sorting requirements are extremely high, and it is probably best to sort out plastics and combustibles which could affect operation of the TD system. MEO is extremely immature at this stage for application on MLLW, and scale-up involves adding more electrochemical cells. Final waste volumes are higher than baseline; but total offgas discharged from all subsystems will be a fraction of the baseline. Relative MEO immaturity could seriously affect project schedules.

System L-1 As in K-1, thermal desorption is the thermal treatment process, this time combined with supercritical water oxidation (SWO) as the liquid organic waste and TD condensed offgas treatment process.

Organic liquid waste, such as sludges and liquefied waste is treated by SWO, as are finely ground and liquefied organic solids. SWO converts input liquid feed into carbon dioxide, water, and inorganic salts. The types of salts depend on the chemical constituents in the feed. The final waste form is grout. The overall system has a much higher technology risk than the baseline system.

SWO would probably be permitted as an aqueous treatment method. SWO produces an offgas stream treated by particulate and carbon filtration. One major advantage is that it requires minimal APC equipment. The DRE of organics from the SWO process has been demonstrated to be within regulatory limits for many organics. Safety, however, is an issue due to the high operating pressures (above 230 atmospheres). The unit has the potential to destroy all organic wastes completely; however, the system is unproven for DOE MLLW. Additionally, the high pressure will create high corrosion and high maintenance costs. It is estimated that with SWO waste feeds being liquid and organic wastes and sludges, only about 3% of the DOE MLLW inventory is represented. The grout waste form represents a higher volume and lower stability than the baseline.

SECTION 4.0

NONTHERMAL SYSTEMS

Unlike thermal systems where all material is simply destroyed, various materials react differently to diverse types of nonthermal treatment. It is important, therefore, to differentiate among the various types of material to be treated. First, the OST support contractor team identified over 400 nonthermal technologies that could be used on various wastes or waste materials (Reference 22). The INTS technical staff then identified one or two candidate technologies for treatment of the major waste components (soils; organic and inorganic sludges; organic and aqueous liquids; soft, complex, and open debris). Soft debris includes, for example, cardboard, plastic, and wood. Complex debris includes contaminated items such as pumps and valves with internal surfaces or cavities that trap contaminants and are not accessible to decontamination agents. Drums, concrete, bricks, glass, and metals with only surface contamination constitute open debris.

4.1 System Descriptions

A summary of the various subsystems utilized in each of the five nonthermal systems is found in the following table:

Table 7. Summary of Nonthermal and Enhanced Nonthermal Subsystems.	DESIG- NATION	PRETREATMENT SOIL/SLUDGE DEBRIS		ORGANIC TREATMENT	STABILIZATION SOIL/SLUDGE DEBRIS		METAL	MERCURY
SYSTEM								
<i>NON THERMAL SYSTEMS</i>								
THERMAL DESORPTION, MEO AND GROUT UNTREATED DEBRIS	NT-1	DESORBER/ NONE	DESORB- ER	MEO	GROUT	POLY- MER	DECON/ GROUT	DESORPTION FOL- LOWED BY LEACHING (D/L)
THERMAL DESORPTION W/ CATALYZED WET OXID (CWO)	NT-2	DESORBER	DESORB- ER	CWO	GROUT	POLY- MER	DECON	D/L
WASHING W/ MEO	NT-3	WASH	WASH	MEO	GROUT	POLY- MER	DECON	WASH
THERMAL DESORPTION, WASH AND ACID DIGESTION	NT-4	WASH	DESORB- ER	ACID DIGESTION	PBC	PBC	DECON/ GROUT	D/L & WASH
THERMAL DESORPTION, WASH (CWO) & GROUT STABILIZ.	NT-5	WASH	DESORB- ER	CWO	GROUT	POLY- MER	DECON/ GROUT	D/L & WASH
<i>ENHANCED NON THERMAL SYSTEMS</i>								
SYSTEM NT-5 W/ GROUT REPLACED BY VITRIFICATION	ENTS-1	WASH	DESORB- ER	CWO	VITRIFI- ER	POLY- MER	DECON/ MELT	D/L & WASH
SYSTEM ENTS-1 W/ VITRIF. OF UNTREATED SLUDGE	ENTS-2	WASH	VITRIFI- ER	CWO	VITRIFI- ER	VITRIFI- ER	DECON/ MELT	D/L & WASH
SYSTEM NT-5 W/ GROUT REPLACED BY POLYMER	ENTS-3	WASH	DESORB- ER	CWO	POLY- MER	POLY- MER	DECON/ MELT	D/L & WASH
SYSTEM NT-5 W/ PELLETIZED WASTE MACROEN-CAPSULATED IN POLYMER	ENTS-4	WASH	DESORB- ER	CWO	PELLETS IN POLY- MER	PELLETS IN POLY- MER	DECON/ POLYMER	D/L & WASH
SYSTEM NT-5 WITH 10 X THE ORGANIC DESTRUCTION RATE	ENTS-5	WASH	DESORB- ER	CWO	GROUT	POLY- MER	DECON/ GROUT	D/L & WASH

NOTES: All secondary wastes and salts are stabilized in polymer. Surface-contaminated metals are decontaminated and metals with entrained contamination are treated in a metal melter

A — Treatment for only organic liquids and sludges

B — Surface contaminated metals are decontaminated and metals with entrained contamination are stabilized in grout or polymer

C — Treatment for organic liquids, organic sludges, and combustible debris

D — PBC = phosphate bonded ceramic (cement)

4.1.1 System 1—Grout Debris Case

Organic destruction is by Mediated Electrochemical Oxidation (MEO). Wastes are pumped into a primary reactor containing an electrolyte of silver (Ag^{++}I) ions and nitric acid. In this highly reactive environment, the organics are broken down into harmless constituents such as CO_2 and water with a 99.99% DRE.

Inorganic sludges and bulk soils are treated in an indirectly heated vacuum desorption dryer to remove volatile organic compounds. Some volatile inorganic compounds (such as mercury) are sent to leaching or ashing operations for remaining trace mercury removal. All three types of debris are grouted without being segregated or treated. In Systems 2 through 5, the debris is treated before grouting.

Metal is sized and then decontaminated in blasting booths. It is then assayed and recycled where possible in the DOE complex. Contaminated liquid is treated and recycled; grit is processed through the residue treatment subsystem.

The grout stabilization subsystem receives treated soil, untreated debris solids, internally contaminated metal waste, lead waste that cannot be decontaminated, and other solid materials from throughout the system. Complex debris is not shredded but put into drums and grouted in place (macroencapsulation). The process assumes disposal in an earth mound and concrete cell concept in engineered disposal units designed in 1991 by Morrison Knudsen (MK) and Chem Nuclear Services. RCRA and non-RCRA disposal requirements are essentially the same, except the double leachate collection system.

4.1.2 System 2—Desorption Case

This system was studied to explore improved debris treatment through vacuum desorption. The key changes over System 1 are an organic destruction subsystem based on catalytic wet oxidation and debris treatment, along with inorganic sludge, process residue, and soil treatment using a vacuum thermal desorber and mercury removal process. Aqueous treatment, APC, metal decontamination, lead recovery, grout stabilization, and polymer stabilization are the same as System 1.

Organic destruction is accomplished with a catalytic wet oxidation process that uses an iron catalyst to enhance oxidation of organic contaminants. Operations take place at 20 psi above atmospheric pressure and between 300° and 400° F.

4.1.3 System 3—Wash Case

This system has several washing approaches for the treatment of process residue and sludge, soil, and debris. Due to the processing of wet, as opposed to dry, solids outputs from residue, soil,

and debris treatment subsystems, these washing approaches have a larger mass throughput. Otherwise, this system is identical to System 1.

4.1.4 System 4—Acid Digestion Case

This system is also a variant of System 1. It was selected for study (1) to examine the use of a strong acid medium to dissolve and subsequently destroy organic wastes and soft debris, and (2) to examine the use of phosphate-bonded ceramic (often called phosphate-bonded cement) as a partial substitute for polymer and grout in the stabilization subsystem.

This system couples acid digestion and 19 other subsystems with the following major differences from Systems 1 to 3: (1) the acid digestion subsystem for organic wastes, (2) the acid digestion subsystem for soft debris, and (3) the phosphate-bonded ceramic subsystem for soils, insoluble salts, process residues, and inorganic sludges.

The phosphate-bonded ceramic stabilization subsystem treats the process residues from the thermal desorber, the organic and soft debris acid digestion subsystems, and treated soil. A polymer is used to stabilize salts such as sodium chloride (NaCl) to reduce leaching as the ceramic is somewhat porous, and grout is used to stabilize untreated complex debris.

4.1.5 System 5—Catalyzed Wet Oxidation Case

System 5 substitutes catalytic wet oxidation (CWO) for treatment of both soft debris and organics to permit a direct cost and performance comparison with System 4.

This system uses vacuum thermal desorption for process residue and inorganic sludge, aqueous wash for soil, high pressure wash for open debris, and grouting for complex debris. As in System 3, the polymer subsystem has a larger throughput than System 1. As with System 4, a slower reaction time is expected and a larger vessel with a longer residence time is required. Most inorganic components in the soft debris are converted to insoluble oxides of salts that are removed from the acid mixture by filtration and sent to polymer stabilization. Treated soil and inorganic debris are grouted.

4.2 Nonthermal Systems Performance

Table 8. Comparison of effluents (all units in lbs/hr)

System	Offgas	Waste Water	Metal to Recycle	Solids to Disposal
Grout Debris, NT-1	696	59	451	4675
Thermal Desorption, NT-2	823	135	451	4616
Washing, NT-3	827	176	451	4468
Acid Digestion, NT-4	1441	780	451	3664
Catalyzed Wet Oxidation, NT-5	1433	564	451	3819
Thermal Baseline, System A-1 (Incinerator)	20697	399	622	1929

Table 9. Comparison of Energy, Reagent Usage (excluding waste stabilization reagents), Total Incoming Transportation Requirements (including waste, reagents, stabilization materials), and Total Outgoing Loaded Transportation Requirements (including waste to disposal and recycled metals to storage)

System	Energy Cost (\$/h)	Chemical Reagent Usage(lb/h)	Trnsportion Incoming (Trucks per	Rqrmnts Outgoing year)
Grout Debris, NT-1	21.35	174	488	462
Thermal Desorption, NT-2	2.72	167	485	457
Washing Case, NT-3	13.21	208	490	456
Acid Digestion, NT-4	2.02	202	443	351
Catalyzed Wet Oxidation, NT-5	1.99	200	456	391

4.3 Nonthermal Systems Cost

Table 10. Total Life Cycle Cost Comparison for Nonthermal Systems (\$millions)

SYSTEM	TLCC
Grout Debris, NT-1	2,637
Therm. Desorption, NT-2	2,608
Washing, NT-3	2,717
Acid Digestion, NT-4	2,952
CWO, NT-5	2,908

4.4 Summary of Technical Evaluations

All five INTS systems provide varying degrees of compliance with both the technical criteria and the tribal and stakeholder principles.

The most aggressive (in terms of organic destruction) treatments can decrease waste volumes by destroying more of the waste. Wastes capable of being completely broken down include organic liquids, organic sludges, and soft or combustible debris. The consequences of oxidizing more of the organic wastes are higher offgas volumes. Also, the more aggressive technologies have less performance risk but require more robust and costly designs to reduce safety risks.

The thermal desorption and washing systems will not adequately remove all organics, and performance assumptions going into the study were usually not met by actual technology demonstrations. Effective removal depends on the organic contaminant and surface characteristics of the waste matrix. The demonstrations did not yield sufficient information to decide definitively whether the systems and technologies will perform as required with modifications to the equipment or operating procedures. The reaction byproducts in the aqueous or gas phases are unknown.

For all the INTS systems, worker and environmental risks (while not quantified in the current study) and the potential of contaminant release in the effluent is reduced by proper system design and operation. The long-term stability of the waste forms is dependent on effective stabilizing operation and proper loading factors of stabilizing agents. Long-term stability must be measured after wastes are produced. At this conceptual design stage, this information is not available.

4.5 System R&D Needs

Most nonthermal technologies are only demonstrated at the bench or laboratory scale. Only three of the 250 nonthermal technologies studied—gas phase corona reactor, vacuum thermal desorption, and washing technologies—are at the small pilot scale level. Before a prototype system can be considered, these technologies must be developed and tested at a size sufficient to validate bench or laboratory scale results. Moreover, application of these technologies to DOE MLLW must be proven.

Many R&D needs identified for thermal systems in section 8.0 are also applicable for nonthermal systems, and the broader applications are spelled out there. However, nonthermal system needs are required in a wider and possibly more basic R&D program to test theories at small scale. Such work spans the gamut of environmental technology R&D, from waste receiving and preparation, to characterization, to sorting and segregation, to material handling, to size reduction, to APC systems, to aqueous waste treatment, to mercury removal, to waste stabilization.

4.5.1 Organic Destruction Efficiencies

In nonthermal systems, the destruction of the organic contaminants is never complete. As much as 1% or more of the incoming organics, or partial decomposition products, could exist in the final waste form. The impact on the long-term performance of the final waste form and migration into the environment is unknown and needs to be determined.

4.5.2 Disposal of Untreated Debris in Grout

Since the stakeholders expressed concern about the long-term safety of untreated debris in the grout final waste form, performance tests of these treatment combinations are necessary before implementation.

4.5.3 Vacuum Thermal Desorption

Vacuum TD requires testing to evaluate the feasibility of vaporizing organics from noncombustible waste for subsequent liquid organic waste treatment. Typical tasks would include:

- Bench scale tests to identify an appropriate desorber design for further testing and to determine if different designs are required as a function of the solid matrix or organic contaminant
- Determination of the fate of mercury, radionuclides, and organics in the desorber
- Ability of the offgas system condensers to remove the volatiles from the stream

4.5.4 System One—Mediated Electrochemical Oxidation (MEO)

This is still a bench-scale technology, and further bench-scale testing and pilot-scale testing will be required to validate the bench-scale work. Tasks are needed to:

- Evaluate the various MEO technologies being developed to assess the most effective and examine those MEO processes based on silver, cerium, and cobalt.
- Evaluate and validate methods for HCl removal from processes using a nitric acid electrolyte or aqua regia in those processes that produce this corrosive reagent.
- Evaluate operating conditions and optimize process design regarding the ratio of feed rates to electrolyte volume, rate of electrolyte circulating, frequency of inert material removal, frequency of electrolyte replacement, and optimum temperature.
- Test the destruction effectiveness of the processes on applicable organic liquids and organic sludges and determine the potential for volatile organics to vaporize before destruction.
- Evaluate the fate of RCRA metals and radionuclides in the MEO processes, verify that they remain in the electrolyte, and validate methods of recycling the metals.
- Demonstrate the recovery of nitric acid from nitrous acid and NO_x produced in the MEO processes and determine the recovery efficiency.
- Determine the flexibility of the MEO processes in the destruction of a wide range of organic compounds from various feeds and determine the maximum acceptable particle size that can be processed.

- Determine the effect of the process on mixtures of organic components, the resulting reaction products, and the secondary wastes produced and determine the potential to produce dioxins.
- Determine the corrosive properties of reagents and reaction byproducts to identify materials of construction.
- Determine how the process performs under upset conditions, the effect this has on the APC system, and how the APC system performs with off-normal quantities of gases and volatile organics.

4.5.5 System Two—Thermal Desorption (TD)

In System 2 all the debris is treated by vacuum thermal desorption, while CWO is used to oxidize organic liquids and organic sludges.

Thermal Desorption R&D needs are the same as those listed in Section 4.5.3 with the addition of the need to resolve issues associated with desorbing debris as follows:

- The TD system included and analyzed in the INTS study is limited to a maximum particle size of less than one inch. A desorber should be developed that accepts larger debris.
- Operating conditions for various feed types. Operating temperatures for combustible debris need to be lower than for inorganic debris to prevent plastics from melting and clogging the system. The feasibility of desorbing high boiling point contaminants, such as PCBs, from combustible debris should be determined.
- Feed sorting requirements to minimize process upsets should also be determined.
- Desorption of combustible debris under a nitrogen atmosphere can generate large quantities of gaseous products, due to volatilization of organic materials making up the combustible debris matrix. The effect of desorbing combustible debris on the offgas system design and the operating conditions for nonplastic combustible debris should be determined.

4.5.6 System Three—Wash Case

R&D needs include:

- Determine extent of waste characterization required
- Validate surfactant selection

- Evaluate ability to remove different contaminants from varied solid matrices
- Determine fate and release of volatile components during washing process

4.5.7 System Four—Acid Digestion

Pilot scale testing is necessary to validate bench scale tests to:

- Evaluate corrosive properties of acid
- Test the destruction effectiveness on organic liquids, sludges, and combustible debris
- Evaluate fate of RCRA metals and radionuclides
- Evaluate methods of recycling acids and metals from the reagent
- Develop methods to separate HCl and nitric acid

4.5.8 System Five—Catalyzed Wet Oxidation (CWO)

Pilot-scale testing is necessary to validate total CWO operation:

- Evaluate destruction efficiency (DE) for mixtures of organic liquids, sludges, and combustible debris
- Evaluate methods to separate precipitated solids from the acid solution
- Evaluate methods to recycle acids and catalysts

SECTION 5.0

SUPPLEMENTAL AND ADDITIONAL STUDIES

5.1 Nonthermal Enhanced Study

In February 1997, the INEEL published an Enhanced Nonthermal Study (Reference 2). This study evaluated the performance and cost of various "hybrid" systems using the same bases as the ITTS and INTS studies:

ENTS-1 is the same system as INTS System NT-5, using catalytic wet oxidation (CWO) except that the treated soil and debris are vitrified instead of being grouted. Treated inorganic sludge continues to be stabilized in polymer.

ENTS-2 is a hybrid thermal/nonthermal system, which is the same as ENTS-1, but the untreated inorganic sludge is vitrified (thermal).

ENTS-3 is a nonthermal system equaling System NT-5 (CWO) except all treated inorganic sludge, soil, and debris are stabilized in polymer.

ENTS-4 is the same as System ENTS-3 except that the treated residue is compacted into pellets and polymer stabilized. More stabilizing agent has to be added to ensure the material making up the pellets adhere, thereby increasing the final waste volume and systems costs.

ENTS-5 is a nonthermal system identical to System NT-5 except the reaction rate of the chemical oxidation process is increased by a factor of ten.

System NT-5 (CWO) was chosen as the basis for the enhanced nonthermal study because catalyzed wet oxidation can treat combustible debris, remove it from the waste stream, and decrease the stabilized waste volume. Detailed comparisons of various system parameters are presented in Reference 2.

Overall, the capital costs for the five enhanced systems were higher than both the thermal and nonthermal systems, while O&M costs were roughly equivalent to the nonthermal systems but higher than the average thermal system O&M costs. Unit costs without disposal for the enhanced systems averaged about a dollar per pound more than the nonthermal systems (roughly \$13 per pound vis-a-vis \$12 per pound) and \$3 to \$4 more than the average thermal system. Disposal costs (\$243 per cubic foot) raised the TLCC for the enhanced systems to between \$3.4 and \$3.9 billion over 20 years. The average TLCC for the five nonthermal systems was slightly over \$3.7 billion. TLCC for thermal systems averaged about \$2.8 billion. Including disposal costs in the TLCC added approximately \$1 per pound for systems producing a glass/ceramic final waste form and added \$3 per pound for systems that use nonthermal primary stabilization, with the attendant polyethylene for secondary waste for both systems.

Improving the reaction rate of the chemical oxidation process (ENTS-5) increased the TLCC by 1%; therefore, there is no incentive to increase R&D expenditures to speed up the reaction rate. This was due to the higher rate of waste feed in the organic destruction process and the associated increase in the size and cost of material handling equipment and ancillary systems to keep pace with the increased reaction rate.

5.2 Portable Systems Study

The INEEL Portable Systems Study (PTS)(Reference 16) was conducted to better define the potential role of portable treatment with respect to DOE MLLW. Portable treatment systems may be an option for smaller quantities of waste at specific DOE sites if shipment to a central facility were not possible. The study first established a representative MLLW for possible treatment by portable systems and formulated portable treatment concepts to treat the selected MLLW. A treatment rate of 2900 lb/hr was used for a 5-year period to treat 8.5 million pounds of MLLW.

The PTS unit treatment costs ranged from \$6 to \$75/lb depending on the specific waste material treated. The composite cost was approximately \$20/lb for treatment of the representative mixed waste in the PTS study. This compared with the ITTS studies for a rotary kiln central facility where the unit costs were \$7/lb. The operating hours for the PTS were assumed to be 800 hours/year compared to the ITTS that used 4032 hr/yr. There are many uncertainties that may impact the cost of implementing portable treatment systems including the same magnitude of investment in meeting regulatory requirements as is made for larger units.

In general, no economic incentive exists for a PTS, but non-economic factors at a site may be influential in the choice of treatments.

The study was conducted in three phases: (1) Waste stream analyses using the Site Treatment Plans which designated planned or existing PTS's to treat MLLW from various sites, (2) formulation of PTS concepts and requirements to serve as the basis for evaluation and comparison, and (3) system evaluation to determine TLCC's for the proposed PTS and for a fixed, centralized facility.

The total PTS cost of four mobile treatment units (MTUs) plus the control trailer was more than \$161 million as opposed to more than \$179 million for the fixed facility. However, other ancillary costs (e.g., site preparation, utility hookups, etc.) raise the total PTS costs to more than \$217 million. Since there is less on-line availability due to required tear-down, decontamination, transportation, and set-up operations, extenuating circumstances must exist to make a PTS economically attractive. However, a central treatment facility may not be capable of handling all special case waste and some centralization of special case waste may be needed in special facilities.

5.3 Replaceable Hearth Study

The OST replaceable hearth study (Reference 15) explored the performance of an "in-can" melter. The replaceable hearth melting approach is a melting and vitrification alternative to the more traditional hearth melting furnace with tapping and casting of molten product into secondary containers. This approach eliminated all tapping and casting functions and associated equipment and eliminated internal hearth refractory maintenance and replacement considerations for a system to treat MLLW. Additional advantages included the ability to input large difficult-to-size-reduce objects and custom-tailor refractory linings for low-volume or difficult-to-treat waste streams.

The study found that glass ceramic container costs are \$500 per cubic meter and \$1000 per cubic meter for nominal container sizes of about 72 inches outside diameter by 72 inches deep (or less). The cost efficiencies generally decrease as container size decreases. By using deeper containers (although there are operational concerns incumbent with such use) the costs are reduced to \$400 to \$700 per cubic meter with depths of 180 to 230 inches. The deep containers also provide for very efficient transport where two containers could load a standard rail car of 263,000 pounds GVW.

The replaceable hearth melter concept eliminates most of the material and labor repair issues associated with hearth type tap and cast melters by using a replaceable container with a disposable refractory lining. These savings are offset, however, by higher container procurement costs and an associated sequence/cycling downtime cost for container undocking, transfer, and new container docking. Total hearth repair and container costs for an industrial-based tap and cast system in an industrial nonradioactive environment are estimated at \$382 per cubic meter for tapping and casting into an assumed 55-gallon drum. Of this amount, materials and labor represent about \$22 per cubic meter and \$330 per cubic meter, respectively. With the added complexity of operations in a radioactive environment, these industrial baseline cost estimates increase to \$590 per cubic meter and \$850 per cubic meter, respectively.

5.4 Cost Savings

Various cost sensitivity analyses were performed on the ITTS and INTS study results (Reference 8). The major conclusions from these analyses were:

- Facility/operating availability is a major factor affecting unit cost
- Shorter operating period with the same volume of waste processed produce only a small effect
- Co-processing of contaminated solid reduces unit costs
- Negligible effect of energy costs

5.5 Comparative Health Risk Assessments

Seven of the ITTS systems and three of the INTS systems were subjected to a comparative health risk analysis (Reference 12) that compared system health risks to the worker and the public when treating DOE MLLW. The risk reduction analyses included assessment of major risk discriminators employing the relative health and safety risks associated with operation of the systems.

Based on preliminary results, the simplified relative risk assessment employed did not identify major differences among the ten systems studied. However, several valuable conclusions were drawn:

- Overall, the risks associated with ITTS technologies were lower.
- Unlike the ITTS, the risks between and among the INTS systems were very similar.
- The risk to workers is higher than the risk to the public—for all systems.
- The dominant risks for all systems were associated with pre-treatment transportation, handling, and storage; pre-treatment sorting and shredding; transportation of hazardous reagents; primary treatment; and disposal.
- Disposal risk was strongly related to the stability of the final waste form produced by specific treatment technologies.
- The lowest risk treatment technologies were those that produced a stable waste form early in the treatment process.
- The risk of transportation of hazardous reagents was a significant contributor to the total risk and was much higher than transportation of either treated or untreated waste. Transportation of treated waste was not a significant contributor to total risk.

5.6 Time and Motion Analysis

This study (Reference 4) was conducted to address the time element in the INTS and ITTS studies. Previous studies focused on material balances, costs, technical effectiveness, regulatory issues, community/stakeholder acceptance, and operability. This analysis explored system dynamics by estimating the treatment time required for a given unit of waste, from receipt to certification for shipping. Labor estimates were developed based on the time estimate for each task, and critical path processes were identified to point out potential bottlenecks in the thermal and nonthermal treatment systems.

The key results were as follows:

- Characterization is a critical path process and very labor intensive
- The differences in receiving and preparation for thermal and nonthermal are less dramatic than estimated in the INTS and ITTS studies
- Material handling is more significant than processing for labor and time
- Special waste treatment is on the critical path for thermal systems
- Debris treatment is on the critical path for nonthermal systems
- Labor FTEs may be about 30% higher than estimated in the INTS and ITTS reports

5.7 Toxic Metals and Radionuclide Partitioning Study

This study (Reference 11) included:

- a) identification of relevant partitioning mechanisms that cause feed material to be distributed among the solid, molten, and gas phases within a thermal treatment system;
- b) evaluations of existing test data from applicable demonstration test programs as a means to identify and understand elemental and species partitioning; and
- c) evaluation of theoretical or empirical partitioning models for use in predicting elemental or species partitioning in a thermal treatment system.

A survey of reported experimental data and results from twenty thermal treatment demonstrations or operating systems revealed the following:

- Partitioning data were generally insufficient in scope and quality to fully characterize all relevant partitioning mechanisms in most systems.
- Data that are typically not obtained include in-furnace measurements such as temperatures, velocities, and compositions of different phases; particle size distributions and size-dependent compositions in feed and offgas streams; and masses or mass flowrates for some streams such as the furnace offgas. It is recognized that there are significant technological limitations in measuring temperatures, velocities, and compositions in high-temperature in-furnace conditions. Reliable technologies and methods for collecting these in-furnace measurements would be useful for obtaining difficult-to-obtain data.
- In order to perform both total and elemental process mass balances as well as identify and quantify the contribution of each partitioning mechanism within a thermal treatment system, the data required to characterize elemental partitioning include mass or mass flow rates and elemental composition of material entering, exiting, or remaining in the thermal treatment system; local temperatures as well as mixing and velocity data in the gas and

molten phase; and, feed and offgas particulate size distribution. Sufficient data are often not obtained to rigorously calculate mass balances for individual elements, species, or total masses.

- Procedures and assumptions that impair mass balance and partitioning calculations include:
  - a) mass and composition of an unmeasured stream calculated by difference;
  - b) sampling measurements that are not representative of the phase being sampled;
  - c) systems at transient rather than steady-state operating conditions; and,
  - d) sample analyses and other measurements that are near or below detection limits.
- Cerium is often used as a surrogate for plutonium and may, in fact, be the best surrogate candidate; however, some test results indicate that plutonium is more volatile than cerium under some test conditions. This could have profound impact on the anticipated requirements on the air pollution control system downstream from the thermal treatment system.
- Some elements exhibit high volatility within a thermal treatment system and, in many cases, partitioning almost completely (greater than 90% feed) exit the system. Mercury and cesium fall in this category. Some elements exhibit very little volatility with any material observed in the air pollution control system (less than 5% feed) attributed primarily to particulate entrainment. Elements that fall in this category include cerium, plutonium, and titanium. Many elements may theoretically fall in one of these two categories but experimentally appear to be more or less volatile based on operating conditions.
- A review of elemental partitioning data from different thermal treatment systems indicates that certain operating parameters can significantly affect partitioning between phases. The extent of elemental partitioning in the waste feed to the air pollution control system as particulate or in the vapor phase is a strong function of the initial element feed concentration, temperature, chlorine content in the waste feed, and waste type. While one or more operating parameters were observed to affect elemental partitioning, not all experimental data necessarily indicated a particular functionality.
- Increases in the feed concentrations that are still relatively low can result in greater volatilization until the local gas phase becomes saturated. This is particularly true with elements with high vapor pressures. However, with low feed concentrations there is also greater potential for experimental error due to sampling and analytical error, feed material segregation, and poor material recovery. This can generate what appears to be higher than normal partitioning to the offgas. Generally, more accurate material balances are achieved with high feed concentrations. Elements where greater partitioning to the air

pollution control system at low feed concentrations were observed include arsenic, barium, chromium, and zinc.

- In a number of cases, a relationship between increased partitioning to the offgas and increasing temperature was observed. This was most readily observed in a series of tests specifically designed to investigate the effect of the operating temperature of the thermal treatment system. From these tests, elements that appear to partition increasingly to the offgas with increasing temperature include silver, aluminum, arsenic, cadmium, cerium, cesium, lead, and magnesium.
- A number of elements exhibited increased partitioning to the offgas when in the presence of chlorine-containing waste. A review of experimental data from different thermal treatment systems indicates that some of these elements include aluminum, arsenic, barium, cadmium, cerium, copper, iron, potassium, magnesium, manganese, sodium, lead, plutonium, and zinc. Elemental feed carryover from liquid waste containing small amounts of metal contaminants with little or no ash contents was reported to be 100% in a rotary kiln incinerator due in part to the atomization of the liquid and the absence of significant bottom ash. In the same system with solid waste types, the percentage of feed elements in the air pollution control system was significantly less with portion of the feed accumulating in the bottom ash.

5.8 Combined Waste Management (WM) and Environmental Restoration (ER) Incineration System Study

This study (Reference 3) was performed to assess alternative treatment systems for contact-handled wastes derived from WM operations and ER activities within the same DOE facility. DOE MLLW consists of a wide variety of organic and inorganic solids and liquids contaminated with alpha and non-alpha emitting radioactive substances. MLLW generated during ER activities is combustible debris, heterogeneous debris, and soil contaminated with non-alpha radioactive substances. Treatment systems are needed to destroy organic material. Other operations are required to stabilize the treatment residues, inorganic materials, and radionuclides prior to disposal in a MLLW disposal facility. WM wastes and their treatment requirements are discussed above in Section 1.0 during the discussion of the background for the ITTS (Reference 7).

The study was performed to explore the cost of treating waste generated by DOE ER activities in combination with the treatment of waste generated from DOE WM operations. It was assumed that ER waste would be treated by an incineration facility similar to those defined in the ITTS study. Two configurations were evaluated: 1) a system (called system ERA-1) similar to ITTS baseline system A-1 (Reference 6), consisting of a rotary kiln incinerator and a vitrifier, and 2) a system (called system ERA-7) similar to ITTS system A-7, utilizing a rotary kiln incinerator operating in a slagging mode, thereby eliminating the need for a primary stabilization unit, and metal melting of the internally-contaminated metal.

The study found that since ER waste was assumed not to be contaminated with alpha material, treating non-alpha waste as alpha waste would require expenditure of funds that could not be justified. Therefore, it appears that the best method of treatment is to keep the two types of waste separated. Combining the alpha and non-alpha systems into a single integrated facility would provide some cost savings by both systems sharing common subsystems. ERA-1 is estimated to save about \$650 million (less than 5% of TLCC), and ERA-7 would save some \$310 million (less than 3% of TLCC).

The small amount of savings may not justify the selection of an integrated facility; however, other factors such as permitting a non-alpha facility more easily than an alpha facility may be a more important driver.

5.9 Proposed R&D Plan for MLLW Waste Forms

This study (Reference 13) was done to recommend a waste form program plan that addresses waste form issues for MLLW. The study compared the suitability of proposed waste forms for immobilizing MLLW in preparation for permanent disposal and related the waste forms to their impact on DOE's MLLW mission.

Waste forms were classified into four categories: high-temperature waste forms, hydraulic cements, encapsulants, and specialty waste forms. Waste forms were evaluated concerning their ability to immobilize MLLW under certain test conditions established by regulatory agencies and research institutions. The tests focused primarily on leach rate and compressive strength. Results indicate that all of the waste forms considered can be tailored to give satisfactory performance immobilizing large fractions of the DOE MLLW inventory.

Final waste form selection will ultimately be determined by the interaction of other, often non-technical factors, such as economics and politics. The study identified three top-level programmatic needs: 1) a basic set of requirements for waste package performance and disposal; 2) standardized tests for determining waste form performance and suitability for disposal; and 3) engineering experience operating production-scale treatment and disposal systems for MLLW.

Finally, the study recommended a waste form R&D program comprised of the following elements (some of which it acknowledged were already being carried out):

1. Performance Evaluation
2. Systems Analysis
3. Waste Form Performance Sensitivity Analysis
4. Waste Inventory Characterization Data
5. Testing Methods Development
6. Testing Methods
7. Natural Analogue Studies
8. Waste Form Optimization

9. Field Testing
10. Verify Waste Form Performance

5.10 Cost Impact of Extended Storage of Alpha MLLW

This study was conducted to discern what problems or opportunities are created by *changes* in (this was an internal INEEL study and is not expected to be published):

- Storage construction
- Waste generation rates
- Treatment volume reduction
- Storage capacity and accumulation
- Availability of new technology systems
- Availability of disposal facilities and disposal rates

The storage cost study included life cycle costs (including costs associated with the storage receiving facility, the waste handling operations, construction and D&D of the facility, treatment and disposal, and transportation from generators to a centralized storage facility) and waste flow analysis. Storage was not considered as an isolated operation; instead, it was included in a broader waste management system. Variables evaluated in the waste management system study included waste inputs from both legacy and newly generated wastes, storage capacity and duration, waste outputs to treatment and disposal, treatment volume reduction (grout or vitrification), and transportation rates to storage from waste vendors.

The study postulated three separate cases which assumed different schedules for the time for development of new technologies and disposal availability:

- Case One: Existing technology
25-years' storage (5 yrs. to construct treatment facility, 20 yrs. to process existing inventory)
Waste is incinerated and grouted
The residue is immediately disposed
- Case Two: New technology developed within 10 years
45-years' storage (10 yrs. to develop new technology, 5 yrs. to construct facility, 20 yrs. to treat inventory, and 10 yrs. to store residue before disposal)
Waste is vitrified
The residue is disposed after a 10-year delay
- Case Three: New technology developed within 20 years

65-years' storage (20 yrs. to develop new technology, 5 yrs. to construct facility, 20 yrs. to treat inventory, and 20 yrs. to store residue before disposal)

Waste is vitrified

Residue is disposed after a 20-year delay

Common Assumptions for all three cases:

- Same waste inventory as MWIR '95 (see Reference 21) totaling 134,770 cubic meters
- Future waste generation at a rate of 5% of existing volume per year for 20 years (total 100%)
- New pre-treatment storage facilities needed and on-line in 5 years
- Existing legacy waste moved to storage during years 5 to 10
- Newly-generated waste stored on-site for 5 years, then shipped to centralized storage in the following 15 years
- Costs for waste transport of treated waste to disposal facility included (500 one-way miles)
- Centralized storage used until all wastes are treated
- Wastes more than 20 years old are output from storage to treatment
- Treatment at same location as central storage
- Treatment technologies are based on ITTS System A-8 (rotary kiln and grout)
- Treated wastes reside in existing storage until disposal is available
- Post-treatment (existing) storage is used until all wastes are disposed

The study found that the costs for MLLW centralized storage range from \$690 million to \$2.2 billion and \$2,500 per cubic meter to \$8,200 per cubic meter. Storage costs are dominated by the O&M component, which is strongly dependent on the length of time in storage. Treated waste returned to storage is less expensive as volume (if vitrified) and operating costs decrease. Post-treatment storage volumes are reduced 56% and operating costs go down 55% when comparing vitrified waste to grouted waste. Further, development of vitrification has the highest payoff if supported early. Vitrification, treatment, storage, and disposal provide a savings of \$556 billion for 45-years' storage, and \$770 billion for 65-years' storage over grout. As the numbers point out, the storage cost savings more than offset the added treatment costs.

6.0 SUMMARY OF MAJOR SYSTEMS STUDY RESULTS

While certain findings of the ITTS, INTS, and ENTS were discussed in Sections 3.0, 4.0, and 5.1, respectively, this section will discuss the major results of these studies.

6.1 Thermal, Nonthermal, and Enhanced Nonthermal Systems

The results of the mass balance calculations and cost analyses are presented in this section for seven thermal systems representative of the ITTS study, the five nonthermal systems evaluated in the INTS study, and the five enhanced nonthermal systems evaluated in the ENTS study. The thermal systems were selected to represent both a combination of some of the most mature thermal systems and some of the innovative thermal technologies under development or demonstration for DOE.

A detailed review of the DOE waste inventory found that only about 20% of the MLLW to be combustible. However, the noncombustible material, assumed to be contaminated with RCRA-regulated materials, requires treatment to meet LDR requirements. Thermal systems, which treat waste at high temperatures and produce vitreous or glass-ceramic final waste forms for disposal and metal ingots for disposal and/or recycling, can treat most of the combustible and noncombustible waste. High temperature processing is capable of destroying all organic material. Inorganic residuals will become part of the ash that is stabilized to a leach-resistant final waste form by either being vitrified in a separate melter, as in three of the thermal systems (A-1, A-2, and H-1), or vitrified in the primary thermal treatment system as in the other three thermal systems (A-7, C-1, and G-1). In System A-8, the residuals are stabilized in grout.

The nonthermal processes for organic destruction, limited to a maximum temperature of 350° C, can process only a small portion of the total waste inventory. Consequently, other unit operations were employed to treat the inorganic materials. Examples include low temperature vacuum thermal desorption and washing which remove organic contaminants for treatment by the organic destruction unit. The residuals are stabilized in grout, polymer, or phosphate bonded ceramic in INTS systems. Two ENTS systems employ vitrification for residual stabilization. For the waste that could not be processed by the thermal or nonthermal main treatment technology, additional subsystem (e.g., mercury amalgamation, metal decontamination, special waste, etc.) were provided so that all of the waste identified in the inventory could be processed.

For thermal systems (ITTS) about 70% of the total waste could be processed through the main thermal treatment unit; whereas, for nonthermal (INTS) and enhanced (ENTS) systems, only 10% to 20% of the waste could be processed through the nonthermal and enhanced nonthermal organic destruction unit. Because of chemical and physical matrix complexity, the nonthermal system required more unit operations to handle all the waste material.

6.2 Liquid, Gaseous, and Solid Effluents

Mass balance calculations performed using the ASPEN PLUS computer code were used to estimate the production of process effluents — gases, liquids, and solids. The mass balance included all incoming waste, process reagents, air, water, soil, or other stabilization agent, etc. Output materials included combustion gases, liquids, and multiple forms of solids including recyclable ferrous metal, amalgamated mercury, and the final disposal waste forms such as glass-ceramic, grout, polymer, or phosphate bonded ceramic. The effluents from these systems are summarized in Tables 11, 12, and 13.

Table 11. Effluent from Selected Thermal Systems

EFFLUENT (LBS/HR)	ROTARY KILN/AIR (A-1)	ROTARY KILN/O ₂ (A-2)	SLAGGING ROTARY KILN (A-7)	ROTARY KILN/GRO UT (A-8)	PLASMA FURNACE (C-1)	ETAL MELTER (G-1)	STEAM REFORMING (H-1)
OFFGAS	20,697	5,874	26,437	20,897	6,895	11,585	11,648
WASTEWATER	399	888	778	-36	463	87	-487
CLEAN METAL TO RECYCLE:	622	22	488	622	658	38	622
CLEAN LEAD	25	25	25	25	25	25	25
CLEAN FERROUS	597	597	463	597	633	613	597
SOLIDS TO DISPOSAL:	1,929	1,929	2,102	3,667	1,861	1,793	1,927
HG AMALGAM	11	11	11	11	11	11	11
GROUT	1	1	1	1	1	1	1
POLYMER	246	246	246	245	246	56	246
SPECIAL WASTE	153	153	153	153	153	153	153
SLAG/GLASS	1,519	1,519	1,692	24	1,451	1,573	1,517
TOTL EFFLUENT (EXCL. CLEAN METAL)	23,025	8,691	29,317	24,527	9,219	13,465	13,088

TABLE 12. EFFLUENT FROM NONTHERMAL SYSTEMS

EFFLUENT (LBS/HR)	GROUT DEBRIS (NT-1)	THERMAL DESORP- TION (NT-2)	WASH (NT-3)	ACID DIGESTION (NT-4)	CATALYTIC WET OXIDATION (NT-5)
OFFGAS	696	823	827	1,441	1,433
WASTEWATER	59	135	176	780	564
CLEAN METAL TO RECYCLE:	451	451	451	451	451
CLEAN LEAD	21	21	21	21	21
CLEAN FERROUS	430	430	430	430	430
SOLIDS TO DISPOSAL:	4,675	4,616	4,468	3,664	3,819
HG AMALGAM	5	9	4	5	5
GROUT	2,913	2,764	2,731	783	1,938
POLYMER	1,602	1,688	1,578	13	1,722
CERAMIC	0	0	0	2,708	0
SPECIAL WASTE	155	155	155	155	155
TOTAL EFFLUENT (EXCL. CLEAN METAL)	5,429	5,574	5,471	5,885	5,817

TABLE 13. EFFLUENT FROM ENHANCED NONTHERMAL SYSTEMS

EFFLUENT (LBS/HR)	REPLACE GROUT W/ VITRIFICATION (ENTS-1)	VITRIFY UNTREATED SLUDGE (ENTS-2)	POLYMER STABILIZATION (ENTS-3)	PELLETIZATION WITH POLYMER (ENTS-4)	INCREASED REACTION RATE (ENTS-5)
OFFGAS	1,701	2,537	1,433	1,433	1,433
WASTEWATER	1,262	941	1,233	1,233	564
CLEAN METAL TO RECYCLE:	605	605	456	456	451
CLEAN LEAD	26	26	26	26	21
CLEAN FERROUS	579	579	430	430	430
SOLIDS TO DISPOSAL:	2,622	2,096	3,231	4,306	3,819
HG AMALGAM	6.7	6.5	4.5	4.5	4.5
GROUT	0	0	0	0	1,938
POLYMER	1,724	349	3,071	4,146	1,722
CERAMIC	0	0	0	0	0
SLAG/GLASS	736	1,586	0	0	0
SPECIAL WASTE	155	155	155	155	155
TOTAL EFFLUENT (EXCL. CLEAN METAL)	5,585	5,574	5,897	6,972	5,816

Most water used in the systems is passed through an aqueous cleanup system and is internally recycled. The aqueous waste treatment system is designed to remove gross immiscible organics, precipitate, and filter inorganic contaminants; destroy soluble organics using ultra violet (UV) photo oxidation; and remove any residual levels of organics and inorganics with activated carbon beds and ion exchange units, respectively. The resulting precipitates are stabilized in polymer.

Performance of the aqueous waste treatment system is expected to meet or exceed regulatory requirements for water discharge. Because water is a product of oxidation, there is a continuous net generation for most systems. The amount of wastewater discharged from the four enhanced systems that use polymer or vitrification for stabilization is higher than systems that use grout because some wastewater is used in the grouting process and is tied up in the grout rather than discharged.

The enhanced systems that use vitrification (ENTS-1 and ENTS-2) have slightly more offgas that do the other enhanced or nonthermal systems. This is because excess air is used in the vitrifier's secondary combustion chamber to oxidize any organics volatilized in the vitrifier. System ENTS-2 has the most offgas because of the organics in the untreated sludge sent to the vitrifier; however, this offgas is still an order-of-magnitude less than the offgas from System A-1 (baseline) and one-third the offgas from system C-1 (plasma furnace).

Metal to recycle is greater for thermal and hybrid systems (ENTS-1 and ENTS-2) that use metal melting for metal debris with entrained contamination and produce ingots that can be recycled. Nonthermal systems macroencapsulate these metal debris items in grout or polymer and dispose of them. This difference is contingent on the assumed technical and economic feasibility of metal recycle and is small in terms of the impact on disposal cost.

The amount and type of stabilized solids sent to disposal is a key discriminator among the technologies. The thermal and nonthermal systems that use grout (or phosphate bonded ceramic) and polymer have substantially higher disposal volumes. Systems NT-4 and NT-5 have less of the final waste form than the other nonthermal systems because soft debris is destroyed instead of being stabilized. The treated and stabilized waste sent to disposal varied from 3,000 to over 4,000 lbs/hr for nonthermal stabilization and from 1,800 to over 2,000 lbs/hr for thermal stabilization processes using vitrification. Approximately equal amounts of secondary residue (i.e., internally-generated salts stabilized in polymer) were produced by both nonthermal and thermal systems. Secondary residue varied from 200 to 400 lbs/hr for nonthermal systems and was approximately 250 lbs/hr for thermal systems. The volumes of waste sent to disposal are summarized in Tables 11 and 12.

Systems that produce a vitrified final waste form have significantly less mass and volume sent to disposal than systems that use a nonthermal stabilization material such as grout or polymer. Production of a glass/ceramic waste form requires one part glass former to two parts waste. Polymer requires one part polymer to one part waste, and grout requires two parts grout material to one part waste. Vitrified waste has a lower total mass than waste stabilized by nonthermal

means because less additives are required to produce the final waste form, and vitrified waste has a higher density than grout or polymer so the volume of waste is significantly less (approximately a factor of three). Thus, hybrid systems, such as ENTS-2 in which all primary inorganic waste is vitrified, minimize both the offgas and the volume of waste sent to disposal. However, not all waste can be vitrified because there are some secondary waste salts that will either cause problems with the vitrifier or will volatilize and, therefore, will not be contained in the glass. These secondary wastes will require nonthermal stabilization such as polymer.

System ENTS-1 has a greater amount of solids sent to disposal than thermal systems because in ENTS-1 treated inorganic sludge (or process residue) is stabilized in polymer. However, replacing grout in system NT-5 with vitrification produces less final waste form volume for disposal. System ENTS-2 has nearly the same amount of stabilized waste as do the thermal systems because most of the solid waste is vitrified in both cases. Replacing grout with polymer (ENTS-3) only slightly decreases the mass and volume of waste sent to disposal because, although polymer uses less additives than grout, the density of polymer stabilized waste is less than grout. System ENTS-4 has the highest final waste form volume because the sintering process that produces pellets requires a one-to-one mixture of clay and waste plus a one-to-one mixture of pellets sintered at 2,200° F to form a dense ceramic structure. If the pellets produced by this process can be shown to pass the TCLP tests, then macroencapsulation may not be required.

The volume reduction factor (Volume In/Volume Out) and the percent of the volume of waste entering the facility that leaves the facility as a final waste form is shown in Table 13. For systems that use nonthermal stabilization the volume of waste is reduced by 5 to 10 percent for those systems that do not destroy soft debris, and by 20 percent for those systems that destroy soft debris (Systems NT-4 and NT-5). The waste volume is reduced by 70% for thermal systems. The volume reduction for System ENTS-3 which uses polymer is also 20%, about the same as NT-5 which uses grout and polymer. There is a volume increase for System ENTS-4 which uses an enhanced hybrid final waste form. Volume reduction for System ENTS-2 is about the same as for thermal systems (~70%).

6.3 Energy Usage

In all cases, energy costs are less than one percent of the treatment costs (i.e., TLCC without disposal). High energy use is associated with systems that operate at high temperatures or use significant amounts of electricity. The highest costs for electrical energy are associated with those systems that use electrical energy for organic destruction (plasma furnace) or to regenerate the oxidizer in the organic destruction process (mediated electrochemical oxidation in System NT-1 and NT-3). Systems that vitrify treated waste use an intermediate amount of electrical energy. Systems that have the highest natural gas cost are those that use combustion for organic.

SECTION 7.0

FACTORS AFFECTING COST

Systems were compared on a total life cycle cost (TLCC) basis over the assumed 20 years of operation, including production and treatment costs. Production costs include all the subsystems required to process the waste including production of the final waste form (but excluding certification and final waste form handling costs). Treatment costs include production costs plus the waste form certification and handling costs. In the following discussion the cost impact of varying the waste loading, volume reduction, system availability, unit disposal cost, delisting, and radionuclide concentration will be evaluated. The selection of a waste form based on cost will depend on production and treatment costs, waste form volume, unit disposal cost, the availability of the treatment system, and the equipment used to produce the final waste form. The interactions among these factors and their affect on system life cycle cost are discussed in the following sections. The sensitivity of costs for both thermal and nonthermal systems due to such factors as capacity and operating time and annual availability are depicted on the following four figures.

Figure 1. Sensitivity analysis by estimate cost components for Nonthermal Systems.

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 2. Results of sensitivity analysis for Thermal Systems.

- 2X Capacity (scaling factor 0.5)
  - Teat Waste Quantity in 10yrs (236 million lb.)
  - Treat 2X Waste Quantity in 20 yrs (472 million lb.)
- Total LCC (\$Million)

10 Year	Baseline	20 Year
\$2,058	\$2,167	\$3,021

Figure 3. Cost Sensitivity to Increased Capacity and Operating Time.

- Total LCC (\$Million)
- Increase operating hours per year from 4032 hrs/yr to 5,850 hrs/yr
  - Reduce operating years from 20 yrs to 14 yrs
  - Increase waste quantity treated in 20 yrs from 236 M lb. to 343 M lb.

Baseline	5,850 hrs/yr; 14 yrs	5,850 hrs/yr; 20 yrs
\$2,167	\$1,794	\$2,239

Figure 4. Sensitivity to annual availability of treatment facility

7.1 Production and Treatment Costs

Waste form production costs include costs associated with treating the incoming waste and producing the final waste form. These costs are insensitive to the volume of the final waste form but are a function of the waste volume to be treated and stabilized. Since all treatment subsystems, except the stabilization subsystem, are identical for the systems considered here, the differences in production costs are due only to the capital and operating costs of the stabilization process. These costs, and the volume of stabilized waste for some of the rotary kiln systems evaluated in the ITTS studies, are shown in the accompanying Table 14.

Table 14. System Production and Treatment Costs

SYSTEM	STABILIZED WASTE VOLUME (m³)	PRODUCTION COST (\$Millions)	CERTIFICATION & HANDLING COST (\$m)	TOTAL TREATMENT COST(\$m)
Rotary Kiln w/ Hi Temp Slag	31,100	1,980	190	2,170
RK w/ Borosilicate Glass	49,700	1,980	300	2,280
RK w/ Grout	71,000	1,840	390	2,230
RK w/ Phosphate Bonded Ceramic	40,700	1,840	250	2,090

Volume is based on the assumption of 67 wt% waste loading in slag, 33 wt% loading in grout and borosilicate glass, and 67 wt% loading in PBC.

Thus, the final waste form volume impacts total treatment costs through the functions of certifying and handling the waste prior to shipment to disposal. For the assumptions used in this study, the baseline cost of stabilization by high-temperature vitrification is approximately \$140 million greater than the cost of grouting the same amount of treated waste. However, certifying and handling the higher volume of grout prior to shipment to disposal costs \$200 million more than vitrified waste. Thus, the total treatment cost using grout stabilization is \$60 million more than the treatment cost using high-temperature vitrification. Changing the vitrified waste form from a high temperature slag to borosilicate glass with 33 wt% waste loading and changing the low-temperature waste form from grout to phosphate bonded ceramic (cement)(PBC), will have little effect on the respect cost of stabilization (e.g., capital and operating cost). However, the differences in waste loading will cause the volume of vitrified waste to increase to about 50,000 m³ and the volume of non-vitrified waste to decrease to 41,000 m³, thereby changing the relative total treatment cost to \$2,280 million and \$2,090 million, respectively.

7.2 Waste Volume

Waste form volume affects total treatment cost through the certification and handling subsystem, and it affects total life cycle cost through the cost of disposal. Waste form volume, in turn, is a function of the waste volume to be stabilized, the waste loading, and the density of the waste form. Waste volume is typically reduced during the treatment process, and the resulting treated waste volume may be reduced or increased depending on the method of stabilization. Conventional wisdom indicates that significant effort should be expended to reduce the waste volume, thereby decreasing handling and disposal volume and cost. However, this may not always be the optimum cost option if the activity of the waste form increases due to volume reduction causing the waste form to exceed the waste acceptance criteria for the disposal site and unit disposal cost to rise significantly.

7.3 System Availability

Treatment costs are also affected by system availability determined by the reliability and maintainability of the system and equipment and the ability to consistently maintain the quality of the final waste form. The treatment costs listed in Table 14 assume equal availability of 46% (i.e., 4032 hours of operation/year). Assuming all other things are equal, increasing the reliability of one of the stabilization technologies, and therefore system availability, can significantly change the relative treatment cost of the systems being compared. For example, increasing the availability of the grout system from 46% to 70% decreases the time required to treat the 360 million pounds of MLLW to 13 years and decreases the treatment cost by approximately \$460 million. Thus, a grout system with 70% availability would cost \$460 million less than a grout system with 46% availability, and \$400 million less than a slag system with 46% availability (excluding disposal costs). Further, unit disposal costs will also affect the choice of waste form based on system availability and the investment decisions to improve system availability. Increasing availability for vitrification or grout systems from 60% to 75% decreases treatment cost and therefore TLCC for either system by ~\$400 million regardless of disposal cost.

However, since the production of grout or PBC uses simpler equipment that may be considered more reliable than vitrifiers, the grout and PBC systems might be expected to have a higher availability. The grout system, with an availability of 70%, has a lower TLCC than a vitrification system with a 50% availability for unit disposal costs less than about \$7,415/m³ (\$210/ft³).

Estimates of system availability may be based on past experience or the maturity of a technology, and improved availability can provide significant savings. However, costs associated with increasing system availability include investment in additional testing to identify flaws in equipment and improvements in equipment design and/or operations, or investing in backup equipment. The latter option will increase capital costs for the additional equipment and increased facility space to house the equipment.

7.4 Delisting

The possibility of delisting certain final waste forms offers the opportunity for cost savings. The assumption in the ITTS studies was that the disposal cost is \$8,580/m³ (\$243/ft³) based on an average size RCRA-permitted engineered disposal facility. However, if vitrified waste produced in the thermal treatment processes can be delisted for the RCRA constituents, the waste would be managed and disposed in a manner consistent with the requirements of the Atomic Energy Act and DOE Orders. Delisting the vitrified final waste form would allow disposal of low-level radioactive waste at an existing shallow land disposal facility at a cost estimated to be roughly one-sixth of RCRA disposal. Applying the shallow land disposal cost to the volume of slag from the vitrification process and the disposal cost of a RCRA engineered disposal facility for the remaining stabilized waste, the total estimated cost of disposal for the systems employing vitrification for stabilization is reduced by as much as \$130 million, or 6% of TLCC.

7.5 Packaging

A waste form in the shape of vitrified marbles has the highest TLCC due to the high production cost associated with vitrification and the high volume associated with packaging uniform sized marbles at a 60% packing factor. The cost of a vitrified monolith may also be penalized if the monolith is formed in a container that, after being subjected to high heat loads, cannot meet U.S. Department of Transportation shipping container requirements or the disposal site waste acceptance criteria. In this case, an overpack would be required thereby increasing the packaging and disposal volume. If the monolith was formed in a 30-gallon container, and a 55-gallon drum was used as an overpack, the packing factor would be about 55% producing a slightly greater penalty in terms of volume than vitrified marbles. However, if an overpack is not required for disposal, then there is no volume penalty associated with disposal of a vitrified monolith.

The void space among the marbles, or between the inner container and the overpack, may be filled with polymer stabilized waste if a physical means of blending the two waste forms was developed. It should be recognized that polyethylene is extremely viscous and will not flow into void spaces. Rather, it must be mixed with particles of another waste form to produce a

combined waste matrix. The volume of polyethylene micro encapsulated waste was only about 10% of the total volume of stabilized waste in the ITTS studies so that the void volume between the marbles is greater than the volume of available polymer stabilized waste at 50% waste loading in polymer. Thus, the cost incentive for filling the void space between the marbles with polymer is the cost avoided by separately disposing of the polymer waste form producing a potential saving of \$4 million at a unit disposal cost of \$706/m³ (\$20/ft³) and \$50 million for a unit disposal cost of \$8475/m³ (\$240/ft³).

7.6 Waste Loading and Unit Disposal Cost

As indicated above, waste form volume affects total treatment cost through the certification and handling subsystem, and it affects TLCC through the cost of disposal. Waste form volume is a function of the waste volume to be stabilized, the waste loading, and the density of the waste form. Approximate densities of the waste forms considered are as follows: slag/glass monolith, 2996 kg/m³; phosphate bonded ceramic (PBC), 2100 kg/m³; slag/glass marbles, 1794 kg/m³; grout, 2035 kg/m³; and polymer, 1282 kg/m³. The density of vitrified marbles is the effective density in a container and based on a 60% packing factor for randomly packed spheres of equal size. Figures 5 and 6 show that waste loading and unit disposal costs affect the relative economies of the waste forms and final disposition. At a disposal cost of \$706/m³ (\$20/ft³), the TLCC of borosilicate glass and grout (at 30% waste loading) are essentially the same within the accuracy of this analysis and for the same availability; whereas, the TLCC for PBC is significantly less than that for high temperature slag (at 70% waste loading).

On the other hand, at a disposal cost of \$847/m³ (\$240/ft³) the TLCC of PBC and slag are identical at 70% wt loading, and the TLCC of borosilicate glass is less than that of grout at 30 wt% loading. In all cases the TLCC for vitrified marbles is significantly greater than the other waste forms evaluated, and the TLCC for grout or glass (at 30 wt% loading) is greater than slag or PBC (at 70 wt% loading). Thus, for the same availability, higher waste loading implies lower TLCC; however, the TLCC of the waste form at a given loading depends on the unit disposal cost.

Figures 5 and 6 display these findings.

8.0 RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

Identified subsystem development needs were as follows:

8.1 Incineration

- Treatability studies using bench-scale systems
- Optimize operation of incineration units by treating surrogate waste
- Prepare detailed cost/benefit analysis for using oxygen in thermal systems
- Improved solids-handling systems for both feed and discharge subsystems
- Improved air exclusion systems for incineration subsystems
- Field tests to determine the accuracy of volatility prediction techniques
- Ash slagging and process parameters to prevent ash slagging

8.2 Air Pollution Control Demonstration

Aspects of the APC subsystem that require development to prove the efficacy of various units within the subsystem include:

- Amount of dioxins/furans formed as offgases are fully cooled
- Analytical requirements
- Mercury removal and pre-HEPA filter designs
- Examination of desirable form and disposition of the mercury
- System design to minimize formation of dioxins and release of metals and PICs
- Bench-scale or small pilot-scale studies of delayed CO₂ release systems and to assess the feasibility and economics of the concept
- Acceptable alternatives to conventional HEPA filters
- Monitoring technologies and techniques
- Effectiveness of dry filters and wet scrubbers on capturing radionuclides and backup carbon filters to remove dioxins/furans and the mercury

The best way to demonstrate the foregoing is to establish an APC test bed in which designs can be tested, subsystem configures can be experimented with, and continuous emission monitors can be evaluated.

Capture of offgas emissions with sampling and delayed release to prevent emission of contaminants did not seem to offer sufficient advantages in the ITTS study to justify their extra cost, but performance data were lacking. Criteria for hold and release need to be established, and performance data are needed to determine if there are sufficient advantages to pursue this approach. However, reliable continuous emission monitors with adequate feedback control and offgas system operation to prevent emissions in case of an upset may eliminate the need for this approach.

8.3 Surrogate Waste Preparation

Development work is needed to produce a mix of nonradioactive waste surrogates that would closely mimic the behavior of wastes in the DOE MLLW inventory. This is important so that "hot" tests can be run on systems and with components that do not require the extensive (and expensive) shielding and other requirements incumbent with treatment of wastes containing radionuclides.

8.4 Front-End Handling

These analyses indicated that front-end handling (receiving, characterization, operating characteristics, opening waste containers, sorting, and size reduction), and material handling in general, have the highest labor requirements, require the most time, are the most costly, greatly affect the operating characteristics of the primary treatment subsystem, and are the major source of worker health and safety risk in the treatment system. R&D in this area would decrease cost and risk and increase throughput. Real-time assay and characterization needs, sorting needs, size reduction needs, and materials handling issues are among the major sources of design and cost uncertainties in the ITTS and INTS studies. These uncertainties indicate a need for increased \$&D in this area. The following areas are recommended for research:

- Gamma and PAN assay: develop methods with reduced assay time and reduced direct observation by an operator
- Material handling bins: develop bins or hoppers that are easily transported, filled from drums, and emptied into feed systems. These bins should be dust and liquid tight
- Sorting and segregation: evaluate sorting and segregation material handling devices on the market for applicability to DOE MLLW
- Shredding: support development of efficient, reliable shredders which need little operator support yet meet process requirements
- Special waste: develop treatment methods for special waste. Determine the effect of potential treatment processes on the size of the facility (including storage requirements) prior to facility design
- Material handling of drums: evaluate improved methods of drum transfer, drum opening, removal of drum contents, drum cleaning, and drum sealing
- Material transfer: develop airlock system which allows for quick transfer of material, possibly by a closed conveyor
- Drum decontamination: develop methods that require little labor. Develop quick assay method
- Polymer stabilization: develop and optimize process to minimize labor. Automate material transfer to reduce handling
- Operating characteristics: develop operating parameters so that the extent of sorting of incoming waste can be established and the size and composition of waste that can be safely fed into the treatment systems can be determined

Additional factors to be considered:

- Feasibility of segregating the inventory developed in the surrogate work
- Availability of robotic systems to determine whether automatic, noncontact sorting equipment is efficient and cost effective and whether the available commercial products could be adapted
- Technologies for handling secondary waste streams from APC systems

8.5 Waste Characterization

Required development work includes:

- Strategies for characterization of the heterogenous waste in the system
- New or refined technologies to meet the needs of DOE after surveying the market
- Testing the selected concepts in a demonstration unit using the following:
  - Nondestructive assay such as neutron activation analysis and real-time organic vapor analysis
  - Specialized neutron interrogation to identify point sources of materials (e.g., mercury)
  - Shredding and bulk storage of wastes to facilitate mixing before sample selection and chemical assays

8.6 Packaging

The following developmental needs are required to give the facility efficient onsite and offsite handling of treated and untreated waste:

- Needs and supply containers required for transporting wastes and intermediate waste forms between sites
- Development and supply of containers for moving special materials (e.g., mercury adsorbent carbon canisters) within the facility
- Performance-oriented packaging for transporting treated waste to disposal

8.7 Vitrification

The following needs relate to the developmental requirements of vitrification:

- Bench-scale tests to select one or two vitrifier designs for a demonstration facility; the primary focus would be understanding, predicting, and controlling the fate of RCRA metals and radionuclides of vitrifying and melting DOE MLLW
- Testing of one or more vitrification technologies in the facility

- Optimizing vitrification technology for the primary stabilization subsystem
- Effect of occluded carbons on the production of a satisfactory glass waste form
- Analysis of the effect of inorganic salts on the vitrification process

8.8 Alternative, Low Temperature Waste Form Stabilization

Although TLCC numbers indicate the value of vitrified forms, such high-temperature processes are expected to produce enough volatile materials to require a separate low-temperature waste form such as polyethylene. Waste forms such as polyethylene will be required to stabilize soluble and volatile metal salts that are difficult to contain in a high temperature glass/ceramic waste form. Tests and data on such separate waste forms are needed to establish their capability to contain radioactive and hazardous materials. The ability to delist all final waste forms and the incentives to do so need to be established. Accurate data for risk assessments are needed to establish the effectiveness of risk reduction by using polyethylene or other low temperature waste forms. Research is needed to develop and test stabilization methods other than vitrification to include:

- Bench scale testing of formulations for primary and secondary stabilization
- Testing and documenting the long-term durability of the waste forms produced by these processes including polymers, polyethylene, sulfur cement, sulfur polymer cement, phosphate-bonded cements, and stabilization of special materials such as mercury and lead
- The effects of surface area (e.g., cracks) on behavior during disposal, including release rates, need to be analyzed. This provides perspective on whether gem-size glass or highly fractured monoliths are preferable or whether the gems should be encapsulated by using the polyethylene fraction from the secondary waste (polyethylene containing the soluble and volatile metal salts) to gain a better or equivalent long-term performance

8.9 Waste Analysis

Development work is needed to identify and develop analytical methods and the instrumentation required. Such work can and should be done with EPA. Such methods and techniques should include:

- Real-time measurement of stack discharges or continuous emission monitors (CEMs)
- Improved methods of determining both the composition and quantity of compounds and components in various gas streams

8.10 Water Pollution Control (WPC) Test Bed

More information is needed on an assembled subsystem that uses the various treatments sequentially to remove suspended particulates, dissolved radionuclides and hazardous materials, and residual organics. The effectiveness of the sequence of treatment steps and the interaction among the treatment steps need to be known for appropriate application of the technologies. In addition, the most appropriate technologies for the treatment of liquids need to be determined unless only systems that do not produce liquid effluent are used.

8.11 Volatilization of Radionuclides and Metals

Volatilization of some radionuclides and hazardous metals in thermal systems will clearly occur. Condensation and capture of these materials as particulate in the offgas system is expected but needs to be verified. More theoretical analysis and experimental data are needed to support application of the systems to various types of waste. A closely related question is the effect of chloride content in the waste on metal volatility and subsequent capture in the APC system. Furthermore, operation under a reducing or oxidizing mode influences the material volatility. Although some data exist, integrated testing and data acquisition to verify the cleaning of gases from MLLW destruction are needed. Volatilization is minor for nonthermal systems.

8.12 Heating Source

All thermal treatment methods require a source of heat, e.g., a plasma torch, induction or resistance heating, flame, or electric arc. The differences in the generation of particulates, volatile metals, and organic destruction from these heat sources may be significant and need to be established to define the performance characteristics and the inputs to the APC and WPC subsystems.

8.13 Oxidizing or Reducing Operation

Major issues due to differences in operating mode that require investigation include:

- reducing atmospheres do not produce dioxins or furans
- management of volatile metal oxides, chlorides, or elemental metals throughout the system varies depending on the operating mode
- determination of effect on achievable destruction efficiency
- post-treatment oxidation of gases before release
- management of operating systems to maintain nonexplosive concentrations of gases

8.14 Future Systems Engineering Analysis

Since many of the bases used in the ITTS and the INTS were fixed for reasonable comparability, parametric variations are required to find out the impact of such variables as operating time, processing rates, waste composition changes, and types of special waste. Additionally, other assumptions that analyze the impact on TLCC such as split operations where some waste types are treated at one site and the rest at another, impacts of transportation and storage, and impacts of variations in disposal requirements need to be evaluated.

8.15 Risk Analyses

Future risk analyses are required to determine if there are any significant risk discriminators among technologies and to put the individual risk factors into a system perspective. These evaluations can then guide DOE policy on implementation decisions and help to avoid future problems with technology selection and public and environmental safety.

8.16 Organic Destruction Efficiencies

In nonthermal systems, the destruction of the organic contaminants in the primary nonthermal treatment unit is usually less than that achieved in thermal units. Partial decomposition products may exist in the treated waste and their presence and characteristics need to be determined for the complex waste streams characteristics of DOE MLLW. The impact of reaction rates on throughput and total destruction and the presence and effect of reaction by-products on the long-term performance of the final waste form is unknown and needs to be determined. A potentially acceptable alternative is to feed the nonthermal residuals to a vitrifier; however, the treatment effectiveness and the acceptable level of organics in the residuals need to be established.

8.17 Waste Loading and Cost Savings

Preliminary analysis has indicated that cost savings can be achieved by using phosphate bonded ceramic (PBC) (as opposed to either vitrified or grout) at higher waste loadings and, especially, as disposal costs increase on a per unit basis. However, more development work is required to ensure the long term stability of the PBC waste form and to confirm through field tests what these paper studies have shown.

9.0 CONCLUSIONS AND OBSERVATIONS

Much important data were developed in the conduct of the systems integration studies that comprised the Integrated Thermal Treatment Systems study, the Integrated Nonthermal Treatment Systems study, and the various ancillary studies that followed. This information should prove helpful to DOE headquarters policy makers, program managers, field managers, and field technology development personnel.

While the studies are not "cookbooks" to plug in technology "X" to meet treatment requirement "Y," they point out the importance of viewing treatment needs in terms of a system. They provide a benchmark to compare MLLW treatment systems to indicate those factors that are important and those that are not.

One observation by the technical team and stakeholder group involved in fashioning the INTS was that DOE has heretofore spent insufficient R&D funds to develop nonthermal technologies. Some DOE sites considered various nonthermal technologies for narrow, specific waste streams and some are continuing to explore their development and application. However, in general, front line field managers tend to make treatment technology choices that select proven technologies to accomplish a specific environmental task by a date certain which are incorporated into a legally-binding Record of Decision date.

The thermal systems studied performed better than the nonthermal systems in terms of cost and destruction efficiency. Nonthermal systems produced more solid wastes to be disposed and cost more but generated less offgas that required treatment.

9.1 Costs

Total life cycle costs (TLCC) associated with nonthermal and enhanced nonthermal systems are 50% to 60% greater than thermal systems primarily due to higher operating and maintenance costs. This difference is significant since these studies should be within plus or minus 30% because of the comparative bases used. Operating and maintenance costs were approximately 50% of the TLCC for both types of systems. Nonthermal systems show (1) greater labor requirements in sorting and separating wastes for treatment in nonthermal systems, (2) the need for more unit operations to treat the various waste streams with greater associated labor costs, and (3) more labor to handle the higher waste volume produced by nonthermal stabilization processes. Disposal costs for nonthermal systems are also higher due to the larger volume of the final waste form produced by nonthermal stabilization processes. TLCC of thermal systems are much less than the life-cycle costs for nonthermal systems, even when nonthermal systems are enhanced with vitrification for waste stabilization.

Enhanced nonthermal systems were studied to learn whether improvements might make the nonthermal systems more economically competitive with thermal systems. As a result, the treatment costs for enhanced nonthermal systems that used nonthermal organic destruction and

vitrification for waste stabilization was approximately 4% less than for strictly nonthermal systems. Although overall labor costs were less, the increased capital and maintenance costs for the vitrification system are nearly equal to this labor savings associated with decreased final waste form volume. The cost for disposal of the final waste form volume is less for vitrified waste when compared to grouted and polymer stabilized waste so that the disposal costs are 60% less. Overall, the total life-cycle cost for the hybrid system (nonthermal destruction of organic coupled with vitrification) is 13% less than all-nonthermal systems.

Doubling the capacity of the baseline thermal system (rotary kiln and grouting of ash and residue, as represented by System A-8 of the ITTS) to allow treatment of the original quantity of waste in one-half the time (10 years) produces a TLCC for the thermal system whose 10-year operating costs are less than 20-year operating costs if waste storage cost is included. Increasing the baseline system availability from 46% (4032 hrs/yr) availability to 67% availability (5820 hrs/yr) decreased the time required to treat the specified quantity of waste by 30% and the associated TLCC by 14%. Increasing the number of treatment facilities from one centralized facility to five facilities throughout the country, with the same quantity of waste distributed among the five facilities, the life-cycle costs will increase by 45% to 240% depending on the scaling factor used to make the comparison.

The costs of the APC subsystem for thermal treatment is only 5% of the total cost for thermal systems. Conceptually, a highly redundant design was used; thus, even the best conceived APC system does not affect the total cost. This is a small investment which is likely to make for a significant positive impact on the local public acceptability of the thermal system.

Treatment of the DOE MLLW inventory in one facility is the most economically advantageous alternative. If the facility availability can be improved over that assumed in the studies through improved equipment and system reliability and maintainability, substantial cost reductions can be achieved.

TLCC are approximately \$2.1 to \$3.9 billion for treating MLLW for the systems considered in the studies. The unit costs for treatment (without disposal) vary between about \$7 to almost \$9 per pound for thermal systems when credit is taken for treatment of contaminated soil as an additive to make vitrified forms of final waste for disposal. TLCC are dominated by the operation and maintenance cost components which are nearly independent of the technology chosen and constitute about 50% to 60% of the total system costs including disposal costs. Since equipment costs are only a small fraction (5%) of TLCC, the cost differences between the treatment systems attributable to equipment are quite small (\$150 million) compared with the total system costs of \$3 billion.

Few significant cost differences exist among the group of thermal treatment systems or among the group of nonthermal systems. Except for the slagging rotary kiln, the lowest cost systems are also the least developed and thus have the most uncertainty and may not have a significant difference if development costs escalate over the assumed 4 percent of TLCC.

The choice of a vitrified final waste form results in lower life-cycle cost compared with polymer and cement-based systems because of the reduced final disposal volume. The vitrified final waste form offers a better long-term environmental performance. Nonthermal systems have higher (~ 60%) life cycle costs than a rotary kiln with vitrification.

The highest cost subsystems are disposal and front-end handling. Operation and maintenance is the highest cost element, followed by disposal, and then by capital costs. About 2% increase in total life cycle costs will provide the best APC subsystem for thermal systems than can be designed with current technology. The investment payoff is in public acceptance.

Because costs within system categories (i.e., between thermal systems and nonthermal systems) are only modestly (~ 5 to 10%) affected by the choice of treatment technologies, reliability, performance, and safety are the most important considerations in selecting systems for treatment of DOE MLLW.

Tables 15, 16, and 17 summarize the costs for the major cost component areas for seven thermal systems, the five nonthermal systems, and the five enhanced nonthermal systems, respectively.

Table 15. Thermal System Life-Cycle Costs (\$Millions) and Percentage of Total Costs

COST COMPONENT	ROTARY KILN/AIR (A-1)		ROTARY KILN/O2(A-2)		SLAGGING ROTARY KILN (A-7)		ROTARY KILN/GROUT A-8)		PLASMA FURNACE (C-1)		METAL MELTER (G-1)		STEAM REFORMING (H-1)	
	COST	%	COST	%	COST	%	COST	%	COST	%	COST	%	COST	%
TEST&DEMONSTRATION	100	4	100	4	100	4	95	3	99	4	88	4	62	3
OPERATIONS BUDGET	97	4	97	4	86	4	101	4	90	4	86	4	99	4
CAPITAL	554	23	536	22	474	21	514	18	459	20	450	21	588	24
O&M	1,362	56	1,379	57	1,227	55	1,463	52	1,283	57	1,220	58	1,390	57
D&D	54	2	54	2	49	2	56	2	50	2	50	2	54	2
DISPOSAL	266	11	266	11	284	13	610	21	259	12	225	11	266	11
TOTAL	2,243		2,432		2,220		2,840		2,240		2,110		2,450	
TOTAL W/O DISPOSAL	2,167		2,166		1,936		2,230		1,981		1,894		2,193	
UNIT TREATMENT COSTS W/O DISPOSAL	\$9.18		\$9.18		\$8.20		\$9.45		\$8.39		\$8.02		\$9.29	
UNIT COSTS W/ DISPOSAL	\$10.31		\$10.30		\$9.41		\$12.03		\$9.49		\$8.98		\$10.24	
UNIT TR. COSTS W/SOIL CREDIT	\$7.85		\$7.84		\$7.01		NA		\$7.17		\$6.86		\$8.90	

Table 16. Nonthermal System Life-Cycle Cost (\$Millions) and Percentage of Total Costs

COST COMPONENT	GROUT DEBRIS (NT-1)		THERMAL DESORPTION (NT-2)		WASH (NT-3)		ACID DIGESTION (NT-4)		CATALYZED WET OXIDATION (NT-5)	
	COST	%	COST	%	COST	%	COST	%	COST	%
TEST&DEMONSTRATION	134	4	142	4	143	4	208	5	167	4
OPERATIONS BUDGET	131	4	129	4	135	4	138	4	139	4
CAPITAL	600	16	561	15	632	17	673	17	668	17
O&M	1,950	52	1,930	53	2,005	53	2,040	53	2,058	54
D&D	74	2	69	2	77	2	80	2	78	2
DISPOSAL	833	22	827	23	799	21	737	19	707	19
TOTAL	3,722		3,658		3,791		3,876		3,817	
TOTAL W/O DISPOSAL	2,889		2,831		2,992		3,140		3,110	
UNIT TREATMENT COSTS W/O DISPOSAL	\$12.24		\$11.99		\$12.68		\$13.30		\$13.48	
UNIT COSTS W/ DISPOSAL	\$15.76		\$15.50		\$16.06		\$16.42		\$16.17	

Table 17. Enhanced Nonthermal System Life-Cycle Costs (\$Millions) and Percentage of Total Costs

COST COMPONENT	REPLACE GROUT WITH VITRIFICATION (ENTS-1)		VITRIFY UNTREATED SLUDGE (ENTS-2)		POLYMER STABILIZATION (ENTS-3)		PELLETIZATION W/ POLYMER (ENTS-4)		INCREASED REACTION RATE (ENTS-5)	
	COST	%	COST	%	COST	%	COST	%	COST	%
TEST&DEMONSTRATION		4		5		4		4		4
OPERATIONS BUDGET	147	4	132	4	142	4	161	4	138	4
CAPITAL	795	21	762	23	660	17	669	15	675	18
O&M	2,134	56	1,878	57	2,108	55	2,450	55	2,023	53
D&D	84	2	81	2	78	2	78	2	76	2
DISPOSAL	484	13	286	9	688	18	911	21	707	19
TOTAL	3,810		3,287		3,832		4,425		3,785	
TOTAL W/O DISPOSAL	3,326		3,001		3,144		3,514		3,078	
UNIT TREATMENT COSTS W/O DISPOSAL	\$16.14		\$13.93		\$16.24		\$18.75		\$16.04	
UNIT COSTS W/ DISPOSAL	\$14.09		\$12.72		\$13.32		\$14.89		\$13.04	

9.2 Cost Saving Opportunities

Up to \$1 to \$2 billion can be saved during treatment of legacy waste and future MLLW by applying systems that minimize disposal volume, minimize the generation of new waste, increase safety and health through more stable waste forms and better operating efficiency, and increase the likely acceptability by addressing other tribal and stakeholder principles (see Section 2.0).

On sites where contaminated soil can be used as the glass former, treatment unit costs (~\$10 per pound before disposal) are reduced by about 10%.

Costs are significantly affected by: (1) operating and maintenance efficiency (~50-60%); (2) characterization, sorting, and preparation (~25-30%); and (3) disposal costs (minimum final volume ~10-20%). Thus, incentives exist to focus on reducing these costs.

Systems that treat and vitrify waste in single operation (slagging rotary kiln, plasma torch, molten metal, and vitrification systems) have the least TLCC.

Costs can be saved if a system is versatile enough to use only one or two technologies to process all waste.

Cost savings can be realized by producing highly stable vitreous type waste forms with low volume.

Savings predicted from application of certain technologies include:

Table 18. Cost Savings Available through Utilization of Alternative Technologies.

SYSTEMS	CURRENT INVENTORY
Steam Reforming and Vitrification	\$320M
Incineration and Vitrification (Rotary Kiln)	\$410M
Plasma Furnace	\$600M
Metal Melter (assuming no metal recycling)	\$690M
Metal Melter (with metal recycling)	\$720M
TOTAL APPROXIMATE SAVINGS	\$0.5 - 1B

BASIS: Baseline system (A-8) using Rotary Kiln incineration and Grout stabilization with TLCC of \$3.4B for DOE MLLW inventory of 230M lbs. current inventory

Some \$430 million in additional savings can be realized by reducing up-front waste characterization and sorting costs by half. Finally, \$370 million in savings can be realized by

improving the overall system availability from the assumed 4,030 hours per year to 5,850 hours per year.

9.3 Performance

The offgas from the nonthermal systems is approximately one-twentieth of the offgas from a rotary kiln with vitrifier, and approximately one-fifth of the offgas from a plasma arc system. Thus, large differences in offgas mass flow can be achieved through selection of different energy sources and methods of treatment, e.g., natural gas heat or electric heat. Although lower offgas mass flows alone do not guarantee a system with lower total pollutant emissions, those with smaller offgas flowrates require smaller and less expensive APC systems even if a highly redundant offgas treatment (air pollution control) subsystem is used to assure minimum emissions of pollutants.

Thermal systems are expected to provide a 99.999% DRE. Nonthermal systems do not have such a requirement. Data on nonthermal systems indicate that up to 1% of the incoming organic materials may be left after nonthermal treatment and must be incorporated in the final waste form. If vitrification were coupled with pretreatment by nonthermal means, improved destruction efficiency should be expected.

Combinations of wet and dry subsystems and the proper sequence of components may minimize dioxins/furans for oxidizing systems. Reducing systems are not expected to produce dioxins/furans.

Regulation of nonthermal units is on a case-by-case basis. About 99% organic destruction will likely result in 1% or more of the incoming organics to reside in the final waste form as carbon -- or as yet to be determined organic material.

The solid waste volume sent to disposal from nonthermal systems is approximately three times the volume from thermal systems using vitrification. Volume of final waste from nonthermal treatments is nearly equal to the original volume of waste. Overall volume reductions, input/output, were about 3.5 for vitrification of the primary waste stream.

Thermal processes will require a secondary low-temperature stabilization process to retain volatile metals and provide for separate disposal of the volatile metals.

The secondary waste from the APC required a separate immobilization step at low temperature, e.g., polyethylene, to contain the materials volatilized from the thermal treatments.

About 70% of the incoming waste is treatable by a thermal process; however, only about 20% of the incoming waste is combustible and treatable by thermal or nonthermal methods. The rest of the waste entering a nonthermal system requires removal of residual organic contaminants prior

to stabilization. Versatility and flexibility are dominant attributes to include in the design of treatment and stabilization operations.

9.4 Versatility

A summary of the studies' findings on systems' versatility is as follows:

- Rotary kiln, plasma arc, and DC arc are near term technologies with good versatility
- Molten metal, molten salt, and steam reforming appear less versatile
- Nonthermal chemical oxidation and super-critical water oxidation have the least versatility

9.5 Regulatory Issues

The regulations for incinerators are well established; however, the regulations for thermal treatments that are not incinerators must be developed by the permitting authority. Treatment technologies that use steam, molten salt, or molten metal for destruction will likely be considered as nonincinerators but will most likely need to meet the regulatory requirements of incinerators.. Some evidence exists that the potential for release of dioxins and furans from these systems is much smaller than with incineration. However, evidence also exists that such pollutants will be removed by the APC systems included in the conceptual systems.

9.6 Comparative Health Risks

In general, the relative health risks associated with ITTS and ENTS technologies were found to be very similar. The risks to workers are higher than the risks to the public for all systems with the dominant risks for all systems due to handling, sorting, and shredding, and transportation of hazardous reagents. Primary treatment and disposal (strongly related to the stability of the final waste form) contribute a relatively small fractions to the total risk. The lowest risk treatment technologies were those that produced a stable waste form early in the treatment process such as slagging rotary kilns and plasma systems.

9.7 Future Development Requirements

- Additional data needed on capability of final polishing carbon filters to stop mercury and dioxins/furans
- Performance of APC subsystems under reducing and steam reforming conditions need to be better known compared to oxidizing conditions

- Characterization of soils that can be included in thermal units as a "glass former" with some reduction in costs
- Successful operation with reduced costs is dependent on the application of monitors, process controls, and final continuous emission monitors that will allow reduction in the front end characterization requirements
- Cost reductions achievable through reduction in final waste volumes by using compositions that have up to 80 weight percent oxides from ash and residues rather than the more customary 20 to 30% achievable through lower temperature glasses
- Long term performance of phosphate bonded ceramics (cements).

9.8 Miscellaneous Issues

- Time and motion studies showed that the differences in receiving and preparation for thermal and nonthermal systems are less dramatic than estimated in the INTS and ITTS studies and that labor cost estimates in those studies may be understated by as much as 30%.
- The storage study found that the costs for MLLW centralized storage range from \$700 million to \$2.5 billion and \$2,500 per cubic meter to \$11,500 per cubic meter. Storage volumes are reduced 64% and operating costs go down 21% when comparing vitrified waste to grouted waste. Further, development of vitrification has the highest payoff if supported early. Vitrification provides a savings of \$674 million for 25-years' storage, \$1.126 billion for 45- years' storage, and \$1.612 billion for 65-years' storage.
- The PTS study evaluated the cost of treating non-alpha MLLW (in contrast to ALL the other studies which assumed alpha handling) scheduled for portable treatment in the site treatment plans (e.g., 8.5 million pounds). The cost of treating this additional quantity of waste in a large centralized system designed to treat all the MLLW in the complex is less than portable treatment by a factor greater than four. There are no significant technical obstacles to applying a portable treatment system on MLLW; however, there are many uncertainties that could affect the cost of implementing portable treatment systems.
- The toxic metals/radionuclides partitioning study showed that there were inadequacies throughout the DOE testing program both in terms of the amount of data acquired in the conduct of the program and the methods for collecting such data. Improvements and suggestions were made as to how to improve this ability

so as to better describe and predict elemental partitioning in a thermal treatment system.

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